AD-A140 601 OPTICAL AND HUMAN PERFORMANCE EVALUATION OF HUD (HEAD-UP DISPLAY) SYSTEMS..(U) AIR FORCE AEROSPACE MEDICAL RESEARCH LAB WRIGHT-PATTERSON AFB.. 1/1

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AFAMRL-TR-83-095
ASD (ENA)-TR-83-5019

OPTICAL AND HUMAN PERFORMANCE EVALUATION OF HUD SYSTEMS DESIGN

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DECEMBER 1983

NOTICES

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COMPONENT PART NOTICE

THIS PAPER IS A COMPONENT PART OF THE FOLLOWING COMPILATION REPORT:

(TITLE): Optical and Human Performance Evaluation of HUD (Head-Up Display) Systems Design.

(SOURCE): Air Force Aerospace Medical Research Lab., Wright-Patterson AFB, OH.

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P003 157	Overview of HUD (Head-Up Display) Optical Designs
P003 158	Measurement of HUD (Head-Up Display) Optical Quality
P003 159	Optical Interactions of Aircraft Windscreens and HUDs (Head-Up Displays) Producing Diplopia
P003 160	Sun/Moon Capture Evaluation
P003 161	Estimating Detection Range and Range Loss Looking through Windshields and Head-Up Displays
P003 162	Direct Performance Assessment of HUD (Head-Up Display) Display Systems Using Contrast Sensitivity
P003 163	Physical Integration of the HUD (Head-Up Display)
P003 164	Future Development Trends for Head-Up Displays

COMPONENT PART NOTICE (CON'T)

AD#: TITLE:

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFAMRL-TR-83-095 ASD(ENA) TR-83-5019
6a. NAME OF PERFORMING ORGANIZATION Air Force Aerospace Medical Research Laboratory 6b. OFFICE SYMBOL (If applicable) AFAMRL/HEA	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) Wright-Patterson AFB OH 45433	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62202F	7184	11	45

11. TITLE (Include Security Classification) Optical and Human Performance Evaluat of HUD Systems Design (U)

12. PERSONAL AUTHOR(S)
Martin, Wayne L. (Editor) - See authors on continuation sheet

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Summary	FROM Nov 82 TO Mar 83	1983, Dec 15	89

16. SUPPLEMENTARY NOTATION
Prepared in cooperation with Air Force Aeronautical Systems Division (ASD) and Air Force Wright Aeronautical Laboratories (AFWAL) personnel. See author listing on cont. sheet.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Head-Up Displays, HUDs, Optical Performance, Human Performance, Human Engineering
05	05		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Eight technical papers, each by a different author, cover several aspects of head-up display (HUD) technology, emphasizing the state-of-the-art and test and evaluation of HUD systems. Authors represent several specialties and laboratories. The papers, by number, cover: (1) An overview of HUD optical design (optics), (2) Measurement of HUD optical quality (optical engineering), (3) Optical interactions of aircraft windscreens producing diplopia (physiological optics), (4) Sun/moon capture evaluation (optics), (5) Contrast loss and target detection (engineering psychology), (6) Assessing HUD performance with contrast sensitivity measurements (biophysics/Psychology), (7) Physical interaction of the HUD (applications engineering), and (8) Future development trends for HUD displays (development engineering).

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Wayne L. Martin	22b. TELEPHONE NUMBER (Include Area Code) (513) 255-7603 22c. OFFICE SYMBOL AFAMRL/HEA

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PREFACE

This report and the majority of effort expended were generated under Project No. 7184, Program Element 62202F, Task No. 718411 and Work Unit 71841145. This program was accomplished during the period of November 1982 to March 1983.

This manuscript is a tribute to the dedication of the authors who gave their full support to the evaluation process described herein. The editor sincerely appreciates those who so diligently gave of their professional talents and time (much of which was during the Christmas holiday season) so that a question of engineering, scientific, and operational importance might be answered to support a timely production decision for the F-16 aircraft. Their identities and affiliations are provided on the following pages. These members of the AFAMRL/ASD/AFWAL team supporting the effort represent a very diverse group of technical specialities. The credit for the organization and superb technical direction of the evaluation team goes to Dr. John C. Halpin (then ASD/ENE Technical Director). The wholehearted support and encouragement of AFAMRL management (Col George C. Mohr, Commander, and Mr. Charles Bates, Director, Human Engineering Division), ASD management (Mr. Fred T. Rall, Jr., ASD/EN Technical Director, Col Barton Krawetz, ASD/EN Deputy for Engineering, Brig Gen George Monahan, F-16 System Program Director, Mr. Ray Johnson, Technical Advisor to F-16 System Program Office) and AFWAL management and contractor support personnel (Col Frank Moore, then AFWAL/FIG, Dr. Keith T. Burnette, Burnette Engineering, and Mr. Paul Garrett, Lear Siegler, Inc.) is gratefully acknowledged.

Finally, since the value of any scientific endeavor lies in its usefulness, it is hoped that the information and methodologies described will serve as both a guide to understanding modern head-up display (HUD) technology, and the means by which that technology might be evaluated.

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INTRODUCTION

Successful night attack missions against ground targets may require the use of a head-up display (HUD) that simultaneously displays both terrain as imaged by a sensor that can "see" in the dark, and a wide variety of symbolic data essential to carry out the mission. Head-up displays with narrow fields of view make it difficult to find targets and other objects of interest and keep them on the display during flight maneuvers. Even acquisition of navigation checkpoints at night, when only sensor images of terrain can be seen by the pilot, is difficult with a narrow field of view HUD. The requirement for a wide field of view led to the acquisition by the Air Force of prototype wide angle HUDs. Early during testing and evaluation of these devices, pilots complained of a variety of problems that had not been present with earlier HUDs that were optically much less complex. It was essential that the reality and the seriousness of the problems be determined. It was clear that doing this would require the united efforts of pilots, development and test personnel, as well as laboratory scientists. Accordingly, a multidisciplinary team of engineers and optical physicists, together with research psychologists and other human factors specialists, was formed at Wright-Patterson Air Force Base. Team members were recruited from several laboratories under the direction of ASD/ENE. The joint participation was later to be regarded as setting a significant precedent for future multidisciplinary, multi-laboratory technical efforts.

Starting with a compilation of pilot comments regarding optical phenomena observed while viewing through the HUD, together with a series of presentations by the optical and system development experts involved, a wide variety of measurements were made using human observers as well as optical and spectroradiometric instruments.

The work was done on aircraft-mounted HUDs at Edwards Air Force Base in California, and on stand-mounted HUDs, both indoors and outdoors, at the laboratories at Wright-Patterson Air Force Base.

During this process it became clear to the team members that HUD technology and associated evaluation techniques were not widely known in the scientific and technical community. Since HUD systems are becoming primary flight instruments, this situation was regarded as deplorable. To help in rectifying the situation, team members wrote a series of technical papers that collectively represented their experiences through the evaluation process and now constitute an introduction to HUD technology and assessment. These papers were used as course notes in a "mini course" given at the IEEE National Aerospace and Electronics Conference (NAECON) in Dayton, Ohio on May 17, 1983. The course title was "Optical and Human Performance Impact of Head-Up Display Systems Design".

These course notes were revised and, in some cases, considerably expanded, and are provided in the present publication as an introduction to HUD technology and an evaluation of that technology from the most important perspective of all, the user's.

OVERVIEW OF HUD OPTICAL DESIGNS

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INTRODUCTION

The Head-Up Display (HUD) and the new technologies being applied to it continue to receive great attention by people considering the functioning of fighter and attack aircraft cockpits. The subject has also received its fair share of attention over the last two years at NAECON as well. Berry and Byrd (1981) described the wide field of view (FOV) HUD being developed as part of the Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) program. Gard (1982) gave a presentation which described the different roles of diffraction optics as used in HUDs and relatively new optical designs which achieve a wider FOV.

This discussion summarizes the material covered by these two papers and serves to form a common basis of understanding of the various HUD technologies. The important features highlighted here figure prominently in the discussions which follow.

COLLIMATION:

When light travels outward from an object, it does so in expanding (diverging) spherical wavefronts. The effect is similar to the ripples in a quiet pond after a stone has been tossed in. We can carry the pond analogy further by placing two bugs relatively close to one another and a short distance from the stone's entry point on the water surface and asking them to face directly into the oncoming waves which they each see. The two bugs will notice that they are not facing in exactly the same direction but instead, they line up on converging vectors which intersect where the stone fell in the pond. Similarly, our two eyes must adjust themselves to converging positions in order to accommodate to the diverging wavefronts of light emitted by nearby objects we look at.

If we return to our two bugs on the pond, but now toss a stone to a place far away from them, they will line themselves up practically parallel with no noticeable convergence in their relative sightlines. As far as our bugs are concerned, what they each see is a straight line wavefront coming from the same direction. In this case, then, the two sightlines are said to be <u>collimated</u>. The sightlines of our two eyes become collimated in a similar manner when we look at distant objects. The flat wavefront which leads to collimated sightlines is also said to be in a collimated condition.

Since the purpose of a HUD is to present information to a pilot without disturbing his fixation on distant objects, it must change the diverging wavefronts of light from its internal image source into wavefronts with the same collimation as those being viewed from the outside world. The optical element which does this transformation, the collimator, can be any type which can bend light rays in the appropriate manner, hence, we can have refractive (lenses), reflective (mirrors), or diffractive (holograms) collimators. Figure 1 shows schematically how each achieves collimation.

Once the display image is collimated, it needs to be combined with the real world scene viewed by the pilot. This is usually accomplished by using either a partial amplitude reflector or a wavelength sensitive diffraction element. Figure 1 shows both of these types of combiners. By the very nature of the process, the pilot always has to look through the combiner element at the real world whenever he wishes to view the overlaid symbology.

Historically, the type of collimator used has determined the generic name of the HUD technology. Hence, a HUD which has a lens type collimator is called a refractive HUD. More recently, refractive HUDs have also become known as "conventional" to differentiate them from the more advanced reflective and/or diffractive element designs.

REFRACTIVE HUDS:

Figure 2 depicts a common refractive HUD layout. The image combiner is typically a 25% reflective coating on a glass plate. One or even two fold mirrors are used along with a relay train optical assembly which transfers image light efficiently from the CRT to the collimating lens. These latter items are usually required to fit the HUD into the available space within the cockpit.

The area over which symbols can be seen in the HUD by one eye at any given time is the instantaneous field of view (IFOV). It is a function of the size of the collimating lens and its distance from the eye (i.e. the IFOV is the solid angle subtended by the lens at the eye). Ideally, the IFOV would encompass all of the FOV desired in a particular application, but the realities of the world do not allow the short viewing distance and/or large collimating lens which this requires. Hence, refractive HUDs are made so that the area covered by an IFOV is only a part of the CRT screen. By moving his eye, a pilot moves the IFOV to any desired part of the CRT screen. The entire FOV obtainable in this way is called the total field of view (TFOV). The visual effect of HUDs that do not form exit pupils (which is typical for refractive HUDs) is very much like viewing the symbols through a knothole in a fence or porthole in a wall. One needs to bob his head about to line the knothole up on the symbol of interest. Since there is separation of the two eyes, each eye has its own IFOV. The two fields usually overlap in an oval region in the center of the perceived IFOV (as shown in Figure 3A). Any symbol in the overlap region is viewed by both eyes. The viewer has a binocular image of symbols in this area, but only a monocular image in the remaining portion of the IFOV. It is this combined IFOV from two eyes which the display community usually refers to when discussing HUD characteristics.

REFLECTIVE HUDS:

If the combiner plate is made into a concave surface, it could perform both the combining and collimation functions simultaneously (Figure 4). Such a reflective HUD has the advantage that the collimator element is above the instrument panel where it can be much larger than a collimating lens and closer to the eye. The IFOV can now be much larger, approaching that of the TFOV. Since the IFOV of each eye is so much larger, the binocular vision overlap area also becomes much larger and covers a majority of the TFOV, as shown in Figure 3B.

There is a fundamental difference in the way the collimator functions which has some direct consequences on viewing characteristics. In the refractive HUD, light from any single point emerges in a collimated beam having the diameter of the lens. The CRT face composes a total viewing field (or permissible head motion limit) which is conical in shape with an included angle equal to the TFOV limits. In the reflective HUD, each symbol uses only a portion of the collimator surface at one time. As a symbol moves over the CRT face, light from it emerges from different areas of the collimator in a collimated beam which is always smaller than the size of the collimator, but the beams are all slanted to intersect at an exit pupil in the cockpit. Within this area or head motion box, all of the symbols can be seen simultaneously, with no head motion required (i.e., the IFOV equals the TFOV).

Any motion outside the head motion box causes the eye to miss substantial portions of the projected beams and the display quickly disappears. The effect is much like viewing the collimated symbols through long tubes, one tube for each symbol. The tubes are tilted so that their axes intersect at the design point (variously called the design eye, working eye, or HUD eye). Each symbol is itself collimated, but the light is travelling along the axis of its tube. The amount one can move before a symbol is blocked by the inability to see down the tube defines the size of the head motion box.

ROLE OF DIFFRACTIVE OPTICS:

Up to this point, no mention has been made of diffractive optics (holograms). This section develops the role diffractive optics takes in modern HUD designs.

The trend in these new designs is to a very wide field of view. With this requirement in mind, one may quickly think of using a reflective HUD. However, in order to minimize optical distortions, the concept shown in Figure 4 would require a very expensive aspheric collimator because of the steep, off-axis angle of the light. The cost of such optical elements is prohibitive and so methods must be found to allow use of spherical elements which are far less expensive.

The idealized case is, of course, to have the CRT at a large distance behind the pilot facing forward and almost directly in front of the combiner element as shown in Figure 5. This ideal situation can be closely approximated by mounting the CRT in an overhead position as is currently being done for commercial transports. If such a configuration used a conventional, partially silvered coating on the combiner, the display brightness would be adequate but marginal. The brightness could be greatly increased if a way could be found to reflect nearly all of the CRT light back to the pilot while at the same time transmitting most of the light from the outside world. Diffractive optical elements can do this more efficiently than dichroic coatings.

The type of diffractive element used in HUDs is a Bragg diffraction stack. It is generated by inducing a series of parallel sheets of alternating refractive index in a layer of gelatin sandwiched between two plates of glass. Light is diffracted according to the classic Bragg diffraction formula ($2d \sin\theta = m\lambda$). The net effect is an angle- and wavelength-selective mirror surface which does not necessarily replicate the physical surface to which it is attached. The Bragg stack is induced into the gelatin via holographic techniques. So-called holographic HUDs which use these diffractive elements do not generate 3-D images, but instead use holography only in the manufacturing of the diffraction elements.

The HUD shown in Figure 5, when using a diffractive collimator, exploits only the frequency/angle selectivity of diffractive optics. If we return to our original reflective HUD concept (Figure 4), but instead use a simple spherical glass element, an effective aspherical reflecting surface can be generated by diffractive techniques. Such a HUD would have the basic configuration shown in Figure 6A. This configuration becomes more practical with the use of diffractive optics, but is not totally without problems. Such diffractive elements with optical power can suffer from undesirable secondary optical effects which cause multi-colored halos to appear around bright light sources. Only recently has problems associated with diffractive elements having optical power been shown to be manageable.

Given that earlier designs had to use diffractive optics with no optical power (i.e., the effective reflecting surface replicated the real surface) only quasi-axial spherical collimator/combiners could be considered. Figure 6B is a simple design that uses only two plates to achieve the condition of light incident on the collimator surface nearly on-axis and from the pilot's side. But,the rear plate is angled so that some light from the bright sky would be selected by the diffraction element and directed to the pilot, causing an unacceptable amount of glare in his line of vision. Another approach is shown in Figure 6C. This design, used in the LANTIRN program, avoids skylight glare directly, but has some secondary "reflections" (really diffractions). A more complete discussion of the design, performance, and limitations of the LANTIRN HUD is given in the Berry (1981) paper.

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1. Berry, Robert L. The LANTIRN Wide Field-of-View Raster Head-Up Display; NAECON proceedings, 1981, pp. 1261-1268.

2. Gard, Jerold H. Holographic HUDs De-Mystified; NAECON proceedings, 1982, pp. 752-259.

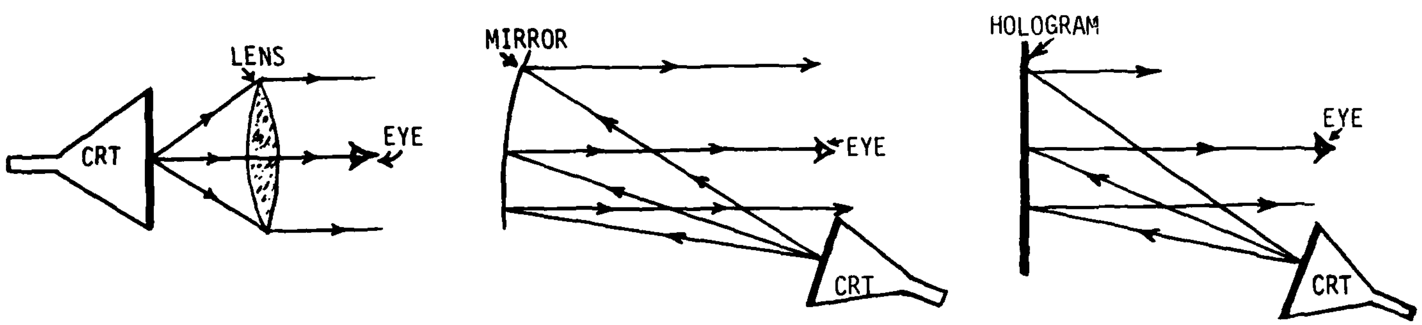

Fig. 1. Three methods of achieving collimation for symbols generated on the face of a CRT. In all cases, the observer is at the right, looking to the left, where he sees the symbols as if they were at an infinite distance.

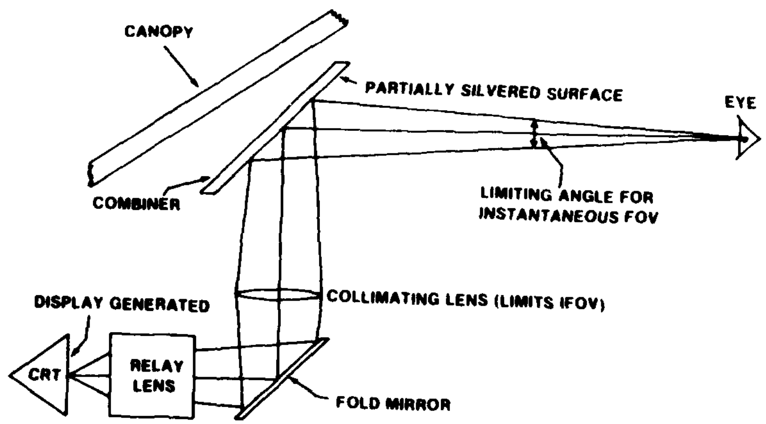

Fig. 2. Collimated symbology is superimposed on images of distant objects by viewing them through an image combiner. Here, the combiner has no optical power and the flat reflecting surface can be partially silvered, be a coated dielectric stack, or be a diffractive layer acting as a plane mirror.

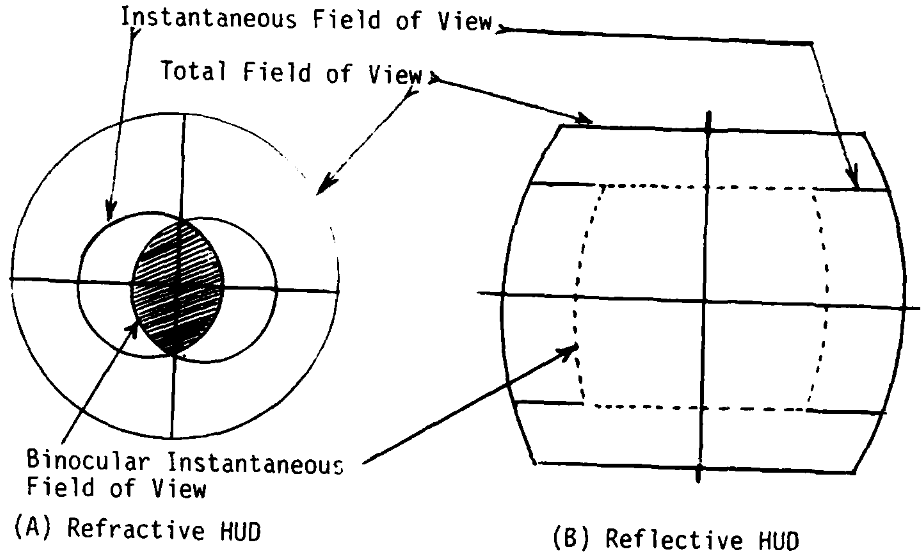

Fig. 3. The relationship between each eye's instantaneous field of view, the binocular (or overlap area) field of view, and the total field of view available for all eye positions (TFOV) for refractive (A) and reflective (B) HUD's.

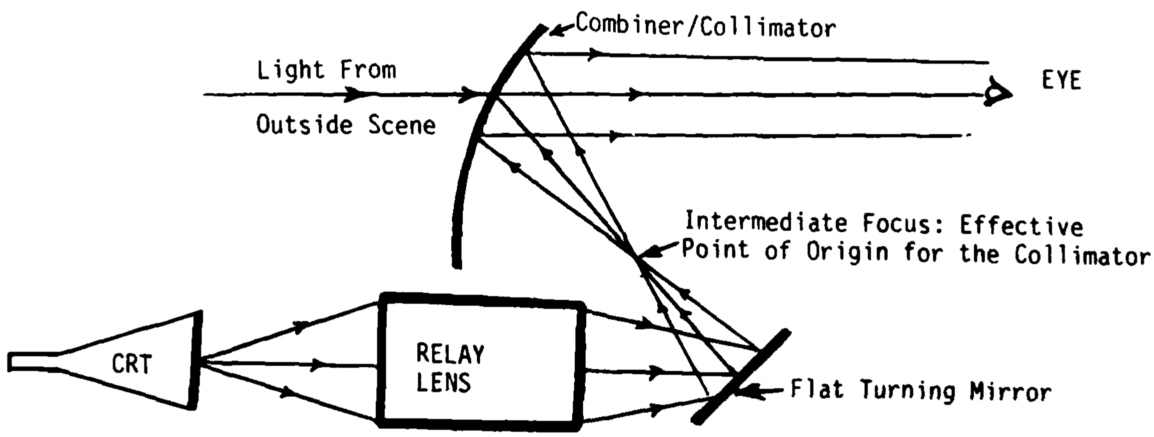

Fig. 4. The collimator in a reflective or diffractive HUD is reflective to light from the CRT and still allows light through from the outside world, it also becomes an effective combiner.

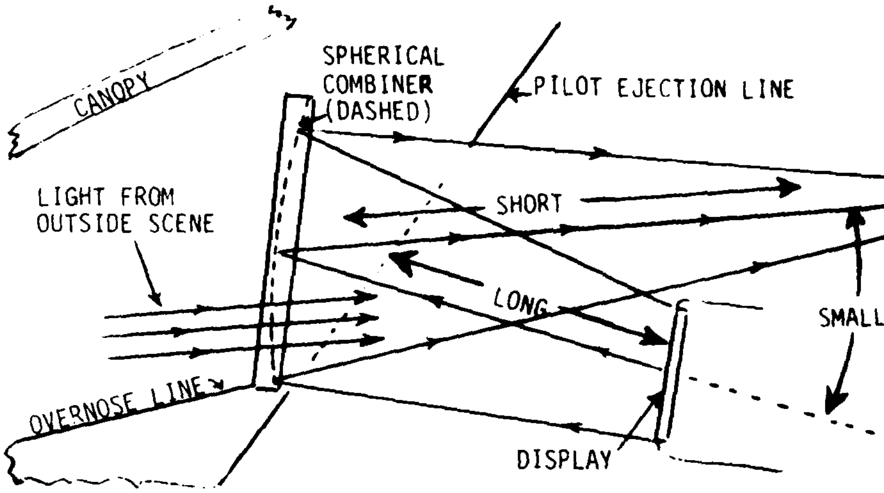

Fig 5. An idealized optical configuration.

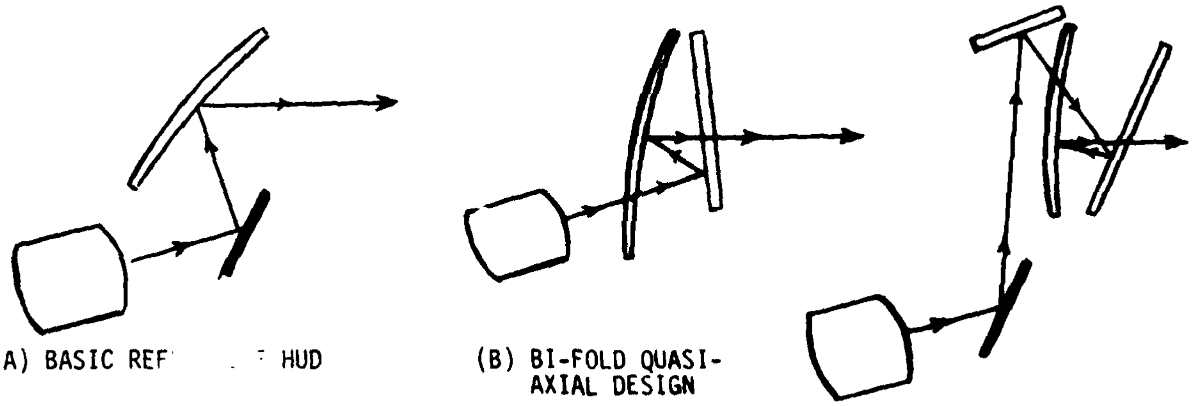

Fig. 6. [illegible] reflective HUD (A) requires an effective aspheric reflecting surface. The bi-fold quasi-optical design (B) requires only a spherical collimating surface, but the flat plate introduces practical problems in a fighter cockpit. Tilting the flat plate the other way eliminates sky reflections and does not violate ejection clearance lines. This tri-fold quasi-axial concept (C) is used in the LANTIRN HUD.

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MEASUREMENT OF HUD OPTICAL QUALITY

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INTRODUCTION

This section describes the optical quality measurement procedures that were adopted to evaluate the LANTIRN HUD. The objective of these measurements was to determine how suitable the HUD optics were for matching human visual requirements. The measurements were directed to the optical components and did not include the cathode-ray tube (CRT) and symbology generation quality.

Measurements fell into two broad categories, those that characterized visual quality viewing through the combiner (effect on outside world target acquisition) and those that concentrated on the visual characteristics associated with viewing the symbology. Table 1 shows the variables that were measured.

Table 1. Image Quality Measurement Parameters

Combiner Effects	Symbology Effects
Modulation Transfer Function (MTF)	Collimation
Optical Power	Image to Ghost Ratio
Spectral Transmissivity	Exit Pupil
Photometric Transmissivity	Reflections
Reflections	

Measurement procedures for each of these parameters will be described with its relationship to and effect on vision.

MODULATION TRANSFER FUNCTION

The MTF of an optical element (combiner) describes the transfer of contrast (or modulation) through the element. It is usually one of the most important quality measures for any imaging system since it can accurately predict the loss in image quality due to the imaging system and therefore accurately predict the loss in visual performance. There are several ways to measure the MTF of an imaging system. The most straightforward way is to input to the system high contrast targets that vary sinusoidally in luminance in one dimension. The contrast at the output end is then measured using a photometer and the ratio of contrast out to contrast in is calculated. This is the modulation transfer factor for that particular sine-wave spatial frequency target. This process is then repeated for other spatial frequencies resulting in a curve of modulation transfer factor versus spatial frequency which is the MTF. Spatial frequency refers to the number of sine-wave cycles per unit length or per unit angle, depending on the application. Since we are interested in the relationship to human vision, the units of cycles per degree are most appropriate for measuring the HUD combiner MTF. Contrast, for all of these measures, is defined as the maximum luminance minus the minimum luminance divided by the sum of the maximum and minimum luminance.

For measuring optical systems it is not easy to produce high contrast, high quality sine-wave targets to directly measure the MTF. An alternate method that makes use of linear systems analysis is equally effective and uses simple square-wave targets. This is the procedure that was used to evaluate the HUDs. A square-wave pattern can be mathematically represented by a series of sine waves as demonstrated by Fourier analysis. By inverting the series it has been shown that a sine wave response (MTF) can be calculated from the square-wave transfer function using equation 1.

$$MTF(f) = \pi/4\{ C(f) + C(3f)/3 - C(5f)/5 + C(7f)/7 \ldots\} \quad (1)$$

where: MTF = sine wave response
f = spatial frequency
C(f) = square wave contrast transfer at frequency 'f'

Normally, the MTF of a planar section of glass (such as a HUD combiner) should have an excellent MTF, i.e. no loss in contrast across the full spatial frequency sensitivity region of the human eye (0 to 60 cycles per degree). However, if there are reflections or light scattering effects, then this will result in a lower MTF uniformly across all spatial frequencies. It is therefore very important to measure the MTF of the HUD under the conditions in which it will be used to include the degrading effects of reflections and light scatter. An alternative is to measure the HUD combiner in a dark room to eliminate these effects from the measurement and mathematically include them later as explicit reflection coefficients. This latter approcach may be preferable since it would then be possible to accurately predict the MTF (and therefore contrast and visual performance) for any ambient lighting condition. This is described in more detail under "reflections".

Figure 1 shows the laboratory set-up used to measure the square-wave response. The photometer (foreground) with a narrow, vertical slit aperture was used to scan the target pattern (Figure 2) with the HUD interposed and with the HUD removed. The MTF of each of these square-wave responses was then calculated. The MTF with the HUD in place (MTF of HUD and photometer) was then divided by the MTF without the HUD (MTF of photometer only) to obtain the MTF of the HUD by itself. This procedure was carried out in a dark room which resulted in an essentially flat MTF (no spatial frequency dependent losses) over the full range of spatial frequencies of the human visual system.

For best (most accurate) results the aperture of the objective lens of the photometer should be no larger than the pupil diameter of the human eye under the luminance conditions of interest (2-3mm diameter for daylight; 7-8mm diameter for night).

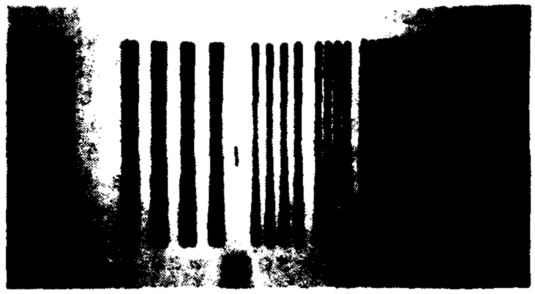


Fig. 1. MTF measurement set-up

Fig. 2. Square-wave target for MTF measurement

If a larger diameter is used then the MTF obtained does not correspond to what the observer will see,but will,in general,be somewhat poorer.

OPTICAL POWER OF COMBINER

If the HUD combiner is indeed a flat plate,then it should have no optical power (no lens effects). However, if the combiner is a curved section, or is formed from glass sections cemented together, then it may contain some optical power. The effect of this optical power may combine with the HUD divergence/convergence errors and the windscreen lens effects to increase or decrease the possibility of diplopia (double imaging; see next paper). The optical power was measured by mapping the angular deviation of light rays passing through the combiner from each eye position as a function of azimuth and elevation. The difference in angular deviation from the two eye positions was then calculated. The angular deviation was measured using the AFAMRL F-16 windscreen movement table and the optical angular deviation measurement device (AFAMRL-TR-81-21), as shown in Figure 3.

Fig. 3. AFAMRL F-16 windscreen movement table and angular deviation measurement device used to measure transmissive optical power.

SPECTRAL TRANSMISSIVITY

For most HUDs the spectral transmissivity measurement is not really required because the combiner coating is usually neutral with respect to wavelength. In other words, it passes a percentage of the light incident on it independent of wavelength. However, if the HUD combiner uses holographic optical elements (HOEs), such as the LANTIRN HUD; or if it has a dichroic or trichroic coating, then the transmission of the combiner needs to be measured for each wavelength resulting in a spectral transmissivity curve. A spectral scanning radiometer and a light box were used to make this measurement. The procedure was to make a spectral scan on the light box by itself then make a spectral scan of the light box through the combiner of the HUD. The second scan was then divided (wavelength by wavelength) by the first scan to yield the spectral transmissivity of the HUD. This process was done in a dark room to insure that reflections did not contaminate the readings. It is important to be careful of the size of the aperture of the radiometer to insure that all the light entering the radiometer has gone through the area of interest on the combiner. In the case of the LANTIRN HUD, the "eyebrow" section was fairly narrow making it somewhat more difficult to measure its spectral transmissivity. Figures 4 and 5 show the spectral transmissivity through the eyebrow and central area respectively of a LANTIRN HUD.

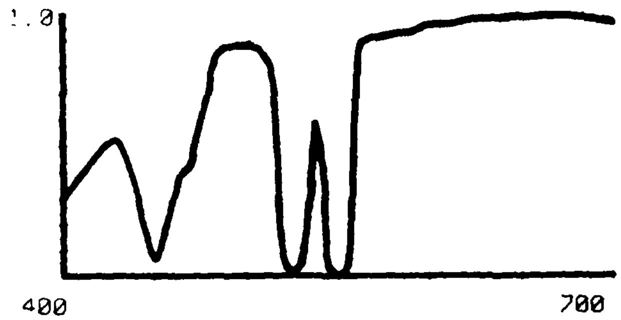


Fig. 4. Spectral transmissivity through the eyebrow portion of a LANTIRN HUD.

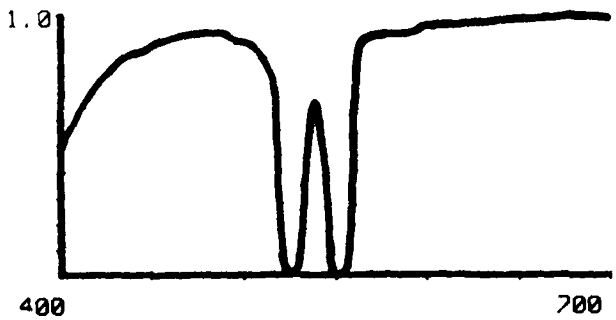


Fig. 5. Spectral transmissivity through the central portion of a LANTIRN HUD.

The spectral transmissivity curve can be used to calculate the photometric transmissivity through the HUD of various objects of differing spectral distributions (colors).

PHOTOMETRIC TRANSMISSIVITY

If the spectral transmissivity of the combiner is flat across all visible wavelengths, then the photometric transmissivity will be the same independent of the color of the object viewed. However, if the spectral transmissivity is not flat (as is in the case of the LANTIRN HUD), then the photometric transmissivity is object dependent. The human visual system is not equally sensitive to all wavelengths of light. Its spectral sensitivity for daylight conditions is referred to as the photopic response curve; which is the basis for photometry. The photopic response curve peaks at about 555 nanometers and ranges from about 400 nm to 700 nm as shown in Figure 6. The photopic transmissivity of the HUD depends on its spectral transmissivity, the photopic curve and the spectral distribution of the object viewed. The photopic transmissivity in equation form is shown as equation (2).

$$T = \frac{\int_{400}^{700} V(\lambda)\ S(\lambda)\ T(\lambda)\ d\lambda}{\int_{400}^{700} V(\lambda)\ S(\lambda)\ d\lambda} \tag{2}$$

where: T = photopic transmissivity
$V(\lambda)$ = photopic sensitivity curve
$S(\lambda)$ = spectral distribution of the object
$T(\lambda)$ = spectral transmissivity of the HUD

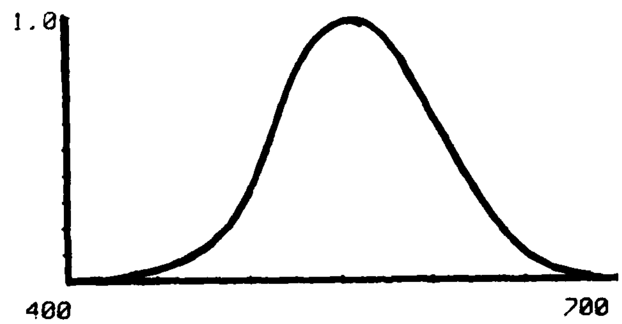


Fig. 6. Photopic sensitivity curve of the human eye.

The spectral distributions of several objects were measured and the photometric transmissivity was calculated for each using data obtained on LANTIRN HUD ser #007 (production versions are expected to be better than the #007 prototype). These are shown in Table 2.

Table 2. Photometric transmission through the LANTIRN #007 HUD for various typically encountered objects.

OBJECT	EYEBROW	CENTER
LIGHT BOX (MEASURED)	54.8%	65.1%
LIGHT BOX (CALCULATED)	54.9%	65.1%
BLUE SKY	46.0%	57.8%
GREEN GRASS	46.8%	57.2%
HAZY HORIZON	49.1%	59.9%
ARMY TANKS	47.6%	58.6%
DISTANT TREES	47.5%	58.4%

The values in Table 2 were calculated assuming unpolarized light coming from each of the objects. In the case of blue sky this is probably not a good assumption. Using the light box and a polarizer filter, the effect of polarization of light on the transmissivity was measured and is shown in Table 3.

Table 3. Effect of polarization on HUD transmissivity

POLARIZATION	EYEBROW	CENTER
VERTICAL	61.0%	70.2%
HORIZONTAL	55.9%	67.8%
NONE	58.4%	68.7%

The windscreen also has a polarization effect on transmissivity that combines and enhances the effect due to the HUD. The net result is an overall transmissivity that may vary by 10 to 15% depending on the aircraft's orientation with respect to partially polarized sky light.

REFLECTIONS

It is difficult to provide a specific measurement procedure for reflections because of the tremendous variations in the types of reflections that occur due to the different optical designs. In general, reflections are unwanted sources of light that are superimposed on the combiner, causing a loss of contrast of both the outside world scene and the HUD symbology. In addition, the reflections may form real or virtual images of interior or exterior objects that act as a distraction to the observer. These reflections should be characterized as to the location of the image, the image source and the relative luminance of the image with respect to the source (reflection coefficient). If the reflection has a different spectral distribution than the source, then it is necessary to measure the spectral reflection coefficient to properly describe the reflection.

It is not possible to cover all these variations in the limited space available in this paper so only one reflection type will be considered to demonstrate the measurement approach to reflections.

In the case of the LANTIRN HUD a reflection occurs from the flat HOE closest to the observer that reflects objects in the knee area of the pilot in the cockpit. This reflection is in a relatively narrow spectral band in the green wavelengths (543nm). The reflection produces a virtual image of the knee area several inches forward of the combiner. A diffuse white light source (≈2700k) was used as a 'target' in the knee area. The luminance of the diffuse light source and its green reflection in the HUD combiner were both measured using a photometer. The reflection luminance was divided by the source luminance to obtain a reflection coefficient (to fully characterize this reflection a spectral reflection coefficient should have been measured). This reflection coefficient varied somewhat across the face of the combiner, but was about 8-10 %. This information coupled with the MTF measurement can be used to accurately predict the contrast loss viewing through the HUD for any given ambient lighting and target luminance condition. Equation (3) shows how this is done mathematically.

$$C = \frac{L_B T_W T_C - L_T T_W T_C}{L_B T_W T_C + L_T T_W T_C + 2RL} \qquad (3)$$

Where:
- L_B = Background luminance
- L_T = Target luminance
- L = Reflection source luminance
- T_W = Windscreen transmittance
- T_C = Combiner transmittance
- R = Reflection coefficient of combiner

If R=0, then there are no reflections and the contrast depends only on the target and background luminance. Note, however, that the resulting target contrast with reflections depends explicitly on the target and background luminances. This means that two targets with identical contrasts with their backgrounds will undergo different amounts of contrast loss for the same reflection situation if their luminances are different.

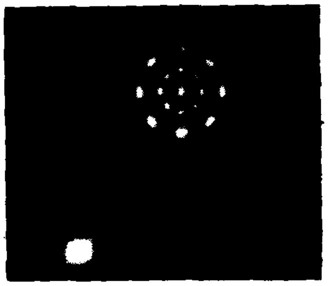
Similar mathematical relationships exist for multiple reflections, chromatically selective reflections, etc. It should be noted that these contrast losses also occur for the HUD symbology, although a slightly different mathematical relationship applies.

IMAGE TO GHOST RATIO

Optical systems, such as HUDs, are typically composed of several optical elements, usually resulting in many air-glass interfaces.

Uncoated glass will typically reflect about 4% of incident light at an air-glass interface. This effect results in unwanted real or virtual images of the object to be imaged (CRT symbology in the case of the HUD). To minimize this effect, surfaces are normally coated with an antireflection coating. This substantially reduces the effect but does not eliminate it. Thus there are usually 'ghost' images that may be visible and distracting to the observer. Figure 7 shows an overexposed photograph of the LANTIRN HUD symbology taken in a dark room. There are several ghost images visible; two near the primary image and one to the right of the primary. A standard measurement (and specification) is the image to ghost ratio. This is determined by measuring the luminance of the primary image and then the luminance of the ghost images. The ratio of the primary image luminance to the ghost image luminance is the image to ghost ratio. In the case of the particular LANTIRN HUD shown in figure 7 this was a very acceptable 300:1 ratio.

Fig. 7. Overexposed photo showing several ghost images on the LANTIRN HUD. Image to ghost ratio was a very acceptable 300:1.



COLLIMATION (DIVERGENCE/CONVERGENCE)

The original concept of a HUD was to place an aiming reticle and critical flight/weapon information in such a position that the pilot could keep his head "out of the cockpit". The HUD symbology was "collimated" so that he did not have to refocus his eyes when switching from looking at the target and viewing the symbology and the aiming reticle would appear at the same optical distance as the target. This eliminated parallax errors between the target and the reticle. Since outside targets are always "far away" the HUD image was collimated or set for optical infinity. As with any physical parameter, there must be some tolerance allowed about the ideal value based on requirements; in this case on the requirements of the human visual system and desired weapon system aiming accuracy. Since the HUD image and outside world target are viewed binocularly, there are two distinct concerns associated with the HUD image optical distance. First, can the eye lens focus on the imagery and the target at the same time? Second, will the two eyes fuse their separate views into one image or two? The first concern is usually no problem; however, the second concern, which also relates directly to parallax errors, and thus weapon system accuracy, is a major concern. This is discussed in detail in the following paper.

The best way to test for collimation is to measure the binocular

OPTICAL INTERACTIONS OF AIRCRAFT WINDSCREENS AND HUDS PRODUCING DIPLOPIA

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Background:

The Air Force is in the process of evaluating new, wide field of view heads-up displays (WFOV HUDs) capable of presenting an enhanced array of visual imagery to pilots of modern aircraft. The wider fields of view through the WFOV HUD optics are achieved by using either conventional optics (as in the AFTI HUD), or holographic optical components (as in the LANTIRN HUD) to enlarge the binocular portion of the field of view (BFOV). In each of these designs, the portion of the FOV available for simultaneous use by both eyes, and the total instantaneous FOV is significantly larger than that found in "standard" HUDs.

The Problem:

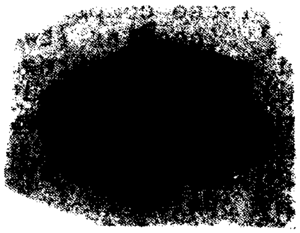
Several pilot complaints have been received concerning double vision (diplopia) experienced while using LANTIRN F-16 HUD serial number 007 in a test aircraft. Specifically, complaint was made of seeing two targets while maintaining a single image of the display-generated aiming symbol. Statements have also been made concerning the doubled appearance of the pipper while maintaining a single image of the target. At least one pilot stated his depth perception was "different", and the world "appeared flatter." These complaints are based on visual errors induced in the pilots' binocular (two-eyed) visual system by the HUD and canopy optics. Not unreasonably, the complaints generated high-level concern about the utility of WFOV HUDs in general, and holographic HUD optical systems in particular. This paper will explain why these visual problems were experienced, and recommend some solutions for any WFOV HUD system, whether it includes holographic optics, as in the LANTIRN system, or "conventional" optics, as in the AFTI system.

The Eye -- Visual Physiology:

Whenever we look directly at an object or target, light from the target is focussed by the eye's optical system to fall on the retina. At the same time, each eye rotates slightly so the images fall on a particular part of each retina called the "fovea." Even though there are two images (one in each eye), we see only one object because nerves from the fovea eventually merge into only one perceptual area in the brain. Each of the two eyes has been mapped to show all possible retinal locations where only one image is perceived when both eyes receive similar appearing images. These retinal locations are called convergence or divergence (vergence) of the HUD. This occasionally gets confusing because a HUD which has a diverging image causes the eyes to converge in order to fuse the image and a converging HUD image causes the eyes to diverge. As noted in the following paper, it is necessary to have a measurement procedure for vergence for both the HUD image and the windscreen "image" of outside objects.

To measure the HUD image vergence, the AFAMRL binocular measurement device was used. This device (AF invention # 14991, December, 1981) was originally developed to measure the alignment of binocular display systems, such as two-eyed helmet mounted displays and was later generalized to HUDs and windscreens. Figure 8 shows a photograph of the device. Two objective lenses in the front simulate the two eyes of an observer. Through a series of beamsplitters and prisms the two images produced by these lenses are combined to form a single image viewed through an eyepiece. A color filter is placed in one side so that the two images can be identified. The two objective lenses are put in the design eye position of the HUD and the HUD symbology is viewed through the device. A moveable mirror is adjusted until the two images of the HUD symbology are 'fused' into one. In this position the device's 'eyes' are converged (or diverged) to intersect at the plane of the HUD symbology. The device is then removed from the HUD and is moved toward or away from some convenient physical object until the two images are again superimposed (the mirror is not adjusted during this process). The angle of convergence is then calculated from the distance between the two lenses and the distance to the physical object. For converging HUDs a slightly different procedure must be used. This general procedure has now been changed by introducing a reticle into the measuement device so that the convergence/divergence can now be read directly from the reticle.

Figure 8. AFAMRL binocular vergence measurement device.



It should be noted that vergence tolerances depend on an individual's inter-pupillary distance (IPD). Those with eyes set wider apart will be more susceptible than those with a smaller IPD.

SUMMARY

Three short observations: Measurement procedures should be standardized. Specifications and measurement procedures should be considered together. Specifications should be based on realistic human visual system capabilities and needs.

"corresponding points." The foveas are an example of two corresponding points. There are many more, distributed symmetrically about each fovea. Whenever fairly similar images are focussed on corresponding points in each eye, we see only one picture. This ability of our visual system to make one perceptual image from two retinal images is called "fusion."

Any well-engineered system is constructed with certain tolerances to error. Our eyes are no different. Each corresponding point has a small area surrounding it (Panum's area) which can tolerate a little misregistration of the image. Although we don't see double if the images fall outside the corresponding points but within Panum's areas, we do see this misregistration as a change in apparent depth of the objects. Images falling on nasal portions of Panum's areas are seen as being farther away in space than images falling on temporal portions. This disparity in the relative positions of similar images falling on each retina is also called "stereopsis" or depth perception.

Depth perception is affected by several cues, but the most important and most sensitive one -- which uses information from both eyes -- is stereopsis. Stereopsis also happens to be the only depth perception cue tested on flight physicals. Figure 1 illustrates how stereopsis works. Assume the eyes are looking at point B, so that target is imaged on each fovea. Light from point A also enters the eye, but is imaged on the retina a little distance from B. Laboratory experiments have shown that if the angle between these two rays of light entering the eye is as small as two seconds of arc, people will see point A as being closer than point B. This misregistration of images on the retina is sometimes called "retinal disparity", or "parallax."

If the parallax angle exceeds a certain amount, the images no longer fall within Panum's Area, and double vision will result. If point A were sufficiently far from point B, an observer looking at point B would see two images of point A. If the observer alternately closed one eye then the other, the image of point A would appear to jump back and forth. This jump or motion parallax is due to the misalignment of the object with our normal lines of sight. You can test this by looking (with both eyes) at a clock or other object on a distant wall. If you place your thumb in your line of sight, you may see two thumbs while you continue to look at the clock. If you alternately close your eyes, you will see your thumb jump back and forth. If it weren't for the built-in tolerances in our visual system, we would always see two images of any object not directly in our lines of sight.

All of this can be summarized: if the optical distances of two targets near our visual axes are relatively similar, we will see the two targets at the same depth. As the difference in these optical distances increases, we begin to experience stereopsis (see depth between the targets). At some point, the parallax is sufficient to cause diplopia or double vision of one of the targets (the one not directly viewed).

The HUD -- Affects Both Symbology and Target Images:

But why should a HUD cause diplopia? The answer is fairly straightforward. HUD imagery is generated on the face of a CRT. Light from the CRT passes through collimating optics so the light rays are rendered parallel. These parallel rays are then reflected from a combining glass to enter our eyes. Parallel light rays cause our eyes' lines of sight to orient themselves so they are also parallel. HUD imagery is seen as a virtual image, hanging in space. (The image is called "virtual" because its light really doesn't come from the place where you see it; here, the light is coming from the HUD rather than the point in space at which it is perceived.)

If the HUD is properly collimated, imagery will be seen at optical infinity, in the same place as the target in the real world. No double vision should be experienced because the images of distant real targets are also formed by parallel rays of light, and there is no parallax between the images. However, if the HUD is improperly collimated, the light rays leaving it may diverge or converge. In any case, if the convergence or divergence is sufficiently different from the parallel rays of light from the target, the images will fall on non-corresponding retinal points, and the pilot will see double images. Exactly which image is doubled depends on what the pilot examines: if he looks at the real world target, the reticle will double; if he looks at the reticle, the target will double. The pilot's visual system has absolutely no choice. If he passed his flight physical vision examination, and if the angular separation between light rays from the target and light rays from the symbology differ by more than a few milliradians of arc, he will experience diplopia of one image or the other.

Fortunately, HUD specifications recognize this possibility, and usually restrict parallax errors to less than three milliradians eye convergence and one milliradian or less eye divergence. Apparently, we can tolerate this amount of misregistration or disparity in "standard" HUDs without seeing double. However, the HUD quality control standards all assume the target is at infinity, so they strive to place the symbology image at infinity. You will see in the next paragraph that the target image is usually not at infinity because of the optical effects of the canopy. The LANTIRN HUD which caused the visual problems also caused a slight convergence of light rays from the HUD symbology, (causing the eyes to slightly diverge in order to fuse the symbology).

The Canopy -- Affects Image of Target Only:

This far, we have seen that diplopia can be caused by the improper collimation the light rays forming HUD symbology. There is another possible cause of diplopia, even when the light from the HUD is properly collimated. The other major cause is the curved canopy. The F-16 canopy is a fairly thick (about 3/4 inch) piece of material consisting of three different kinds of plastic (in the laminated version), or an equally thick sheet of polycarbonate (in the monolithic version). Each of the current vendors manufactures his canopies using methods which result in parts which are optically different from each other. One optical effect common to all curved canopies is the formation of a very weak "minus" or "negative" or "concave" lens in the forward area. Concave lenses cause previously parallel light rays to become divergent. In some canopies, this moves the optical position of the object from infinity to as close as 40 feet. The canopy on the aircraft with the LANTIRN HUD caused a slight divergence of light rays from the target, as if they came from a distance less than optical infinity.

But why don't we see double when we look through currently accepted F-16 canopies without interposing a HUD in our line of sight? A question fairly easy to answer. Our eyes adjust by turning slightly inwards to image the deviated rays on corresponding retinal points. Since all the rays are deviated more or less equally, and since there is no undeviated reference image, our eyes' tolerances accept the canopy-transmitted image of the world. Sometimes the world looks a little blurry or wavy, but we usually don't see double. If our pupils were very much larger, if the canopy were a little worse, or if conflicting image information were present at the same time, we would indeed experience diplopia.

HUD + Canopy + Eye Optical System:

Figure 2 shows how the HUD affects both light from the target (by refraction) and light from the CRT (by reflection). The canopy affects only light from the target (by refraction). If the canopy-induced vergence of light rays from the target is sufficiently different from the vergence of the light rays from the HUD symbology, diplopia will result. In other words, diplopia can be experienced when looking through either a perfectly collimated HUD and a canopy with some measurable parallax error, or a misaligned HUD and a "perfect" canopy. Specifying perfect parallelism of HUD-generated light rays is not necessarily the goal. The goal should be the attainment of comparable vergence effects of canopy and HUD on both target and symbology.

Measurements of the transparency and LANTIRN HUD aboard the F-16A which caused the pilots to complain of diplopia revealed that the LANTIRN HUD vergence error and the canopy vergence error were additive. Pilots flying this aircraft experienced more than five milliradians parallax error between target and symbol through certain portions of their field of view.

The optical effects of pupil-forming and non pupil-forming systems (holographic HUDs and conventional HUDs) are covered elsewhere in the Proceedings, as are relative advantages and disadvantages of wide instantaneous overlapping fields of view.

Suffice it to say that the smaller the instantaneous overlapping FOV, the less the opportunity to see double because diplopia is experienced only while the eyes are in the overlapping IFOV. Of course, the converse is true -- large overlapping IFOVs increase the probability of seeing double if there is a parallactic error somewhere in the system.

At present, all F-16 canopies are measured to determine how much angular deviation they will impart to a light ray passing through the canopy. This sighting error measurement is made only from the cyclopean eye position, located near the cockpit "design eye." All current USAF pilots have two eyes, located about 65mm apart (about 1.25 inches on either side of the cyclopean eye position). This separation of our eyes means our lines of sight pass through the canopy about 2.5 inches apart. Because of the minus lens effect mentioned in the previous paragraph, and because of the point-to-point variability in angular deviation within any single canopy, each eye then experiences a different vergence vector when viewing objects external to the cockpit. This vergence vector varies as the pilot looks around the field of view available for binocular vision. As indicated previously, our eyes are extremely sensitive to these tiny vergence-induced retinal displacements. At the present time, no canopy specification for any current USAF aircraft include vergence (collimation or parallax) limits similar to those included in HUD specifications.

Some Solutions

Several possible solutions may be considered, including introducing more stringent optical specifications for canopies, substituting flat-plate windscreens for curved transparencies, and reducing the binocular field of view of the HUDs. The best solution appears to be one which considers both canopy and HUD optics as a system, with specified limits of binocular parallax for the entire system rather than for each of the components. This could allow canopies and HUDs to be matched so their errors could cancel each other out to some extent. The logistical problem associated with this proposal is not trivial as each canopy's specifications would have to be matched with an appropriate HUD, within certain tolerances. However, each F-16 canopy is presently measured for "nameplate values" to input to the fire control computer of the particular aircraft on which it is mounted.

Measurement of the F-16 canopy-induced parallax can be done with equipment similar to that in use for measuring F-16 angular deviation. The measuring instrument should be located so it scans from points about 1.25 inches on either side of the cyclopean eye position. Angular deviation data from each matrix of values obtained from right and left eye positions can then be combined to show the disparity or parallax for each viewing angle. Of course, the effects of lateral displacement would introduce an error in these calculations, so only "pure" angular deviation should be measured.

Marconi Avionics have indicated that they could adjust the vergence of their WFOV HUDs to correspond with the vergence effects of the "average" F-16 canopy. If the remaining individual canopy errors exceeded the visual system's tolerance, an additional lens or other optical modification could be made to match the HUD to the canopy. The Air Force Aerospace Medical Research Laboratory (AFAMRL) has measured a series of F-16 canopies to determine their binocular disparity, and is now cooperating with the F-16 SPO and Marconi Avionics to determine whether a single correction would suffice for the majority of WFOV HUD-Canopy combinations. The tolerances allowable for the system depend on the visual systems' ability to maintain a single image when the canopy and WFOV HUD optics cause some parallax error. Unfortunately, tolerance limits of this type have not as yet been determined for the specific conditions encountered with aircraft WFOV HUDS and canopies.

Published threshold values are either questionable or gathered under circumstances inappropriate for generalization to F-16 HUD application. Thus, the F-16 SPO asked AFAMRL to conduct its own study.

Test Objectives

1. To determine the limits of the region of single vision as indicated by the horizontal diplopia thresholds of positive and negative disparity.

2. To determine the extent and nature of the distribution of individual differences in a Flying Class II Vision Population.

General Methods: Experiment

Definition: Optical distance is expressed in terms of the angular deviation of the eyes from the straight-ahead. Positive disparity means that a non-fixated object is optically nearer than a fixated object. Negative disparity means that a non-fixated object is optically farther than the fixated object. The diplopia effect threshold is that degree of disparity which induces a report of double vision <u>or</u> a binocular suppression effect on 50% of its presentations to an observer.

Equipment: The equipment consisted of a computer controlled HUD emulator which could superpose a luminous line (symbology) on a distant, out-the window scene. The optical distance of the symbology was adjusted to be either nearer or farther than a conspicuous vertical structure (a light pole) in the scene.

Subjects: A total of 32 persons were tested. All were volunteers from AFAMRL, ASD/EN and ASD/YP. All met at least Flying Class II Vision Standards and, further, none wore contact lenses, since pilots may not wear them.

Task: On each trial, an observer fixated a distant target and indicated whether or not a briefly-presented luminous line (the superposed HUD symbology) appeared single or double. Another response, that a single line appeared but was misaligned with the target, was possible and indicated that the view from one eye was being suppressed.

Threshold Conditions: Four thresholds were determined for each subject, one at each crossing of two disparity directions (positive and negative), with two viewing exposure times (100 msec and 3 sec).

Threshold Determination: Thresholds were determined with a maximally efficient threshold bracketing technique.

Results and Discussion

The main findings of this study are: (1) observers are relatively intolerant of negative disparity, (2) longer viewing is more likely to lead to a diplopia effect than very short glances, (3) resistance to disparity appears to be an individual trait, and (4) a large proportion of responses involve suppression of the view from one eye. The overall median negative disparity threshold was 1.2 mrad and the overall positive threshold was 2.6 mrad. These values are recommended as the maximum disparities acceptable for wide-field-of-view Canopy-HUD optical systems. Since the values are so small, we further recommend that the canopy and HUD be treated as a system, with technical interaction between the vendors, and between the vendors and the USAF. The disparity values indicate the net difference between both system components, so optimization may be possible by appropriately matching the optics.

Further details may be found in a forthcoming AFAMRL Technical Report by R. Warren, T. Connon, L. V. Genco, and H. L. Task.

SUN/MOON CAPTURE EVALUATION

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INTRODUCTION.

Because of their optical characteristics, head-up displays (HUDs) have always interacted with various kinds of sunlight to produce unwanted reflections.

"Capture" means that a HUD can and will capture or trap light and direct it into a pilot's eyes. This capture effect can result in both reflections and retroflections. Reflections occur when an external light source impinges on a reflective surface. Retroflections are light reflections that result from external light entering the HUD optics train, reflecting off the face of the cathode ray tube (CRT), and passing back out through the optics. Both the reflected and the retroflected image are called reflexes.

With the introduction of diffractive optics technology, there is a need to describe how diffraction and conventional optics perform in the presence of collimated light sources, such as that provided by the sun and moon.

EVALUATION OF CAPTURE CHARACTERISTICS.

The capture evaluation was intended to determine the susceptibilities of conventional and diffractive HUDs to external light sources. Two different conventional HUDs and one diffractive HUD were evaluated. The test setup in Figure 1 provided a means of moving a collimated fiber optic (artificial) sun through a constant arc in front of, behind, and to either side of the HUD.

A string was tied to a point at mid combiner and used to provide a constant distance for the fiber optic light source. A video camera was positioned at the design eye location to look through the HUD combiner at an eye chart as the artificial sun was moved. The angle between the video camera and the HUD combiner was adjusted to duplicate the A/C installation.

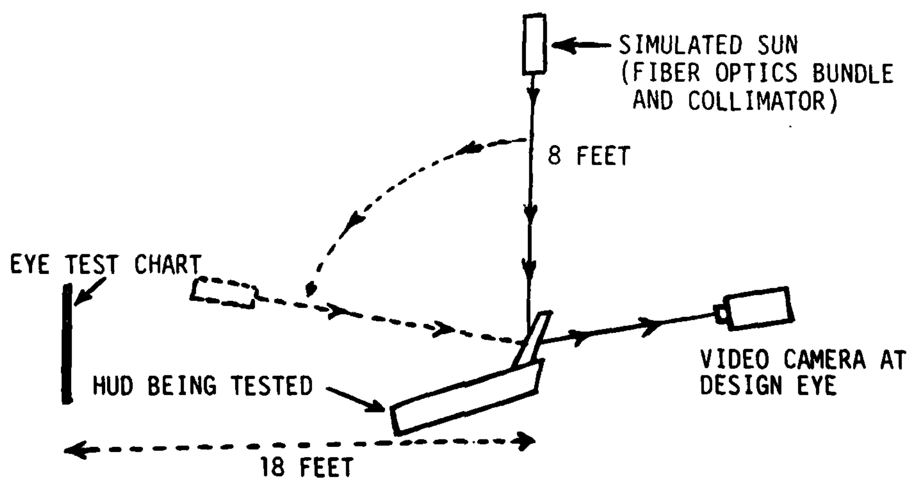

Fig. 1. Lab set up for measuring HUD capture characteristics.

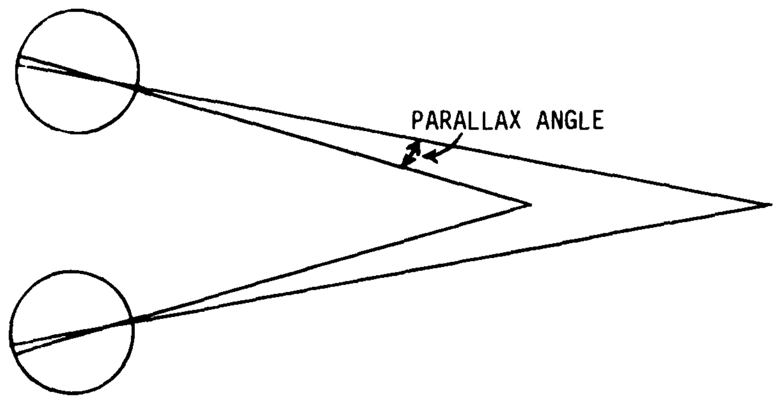

Figure 1. Parallax angle and stereopsis

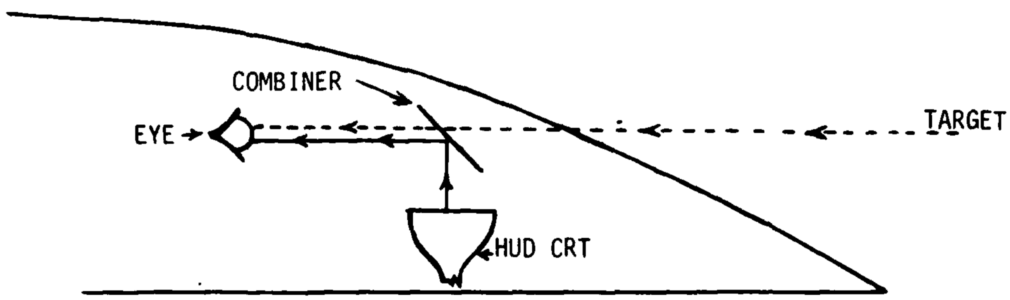

Figure 2 A. The canopy affects light from only the target. (side view)

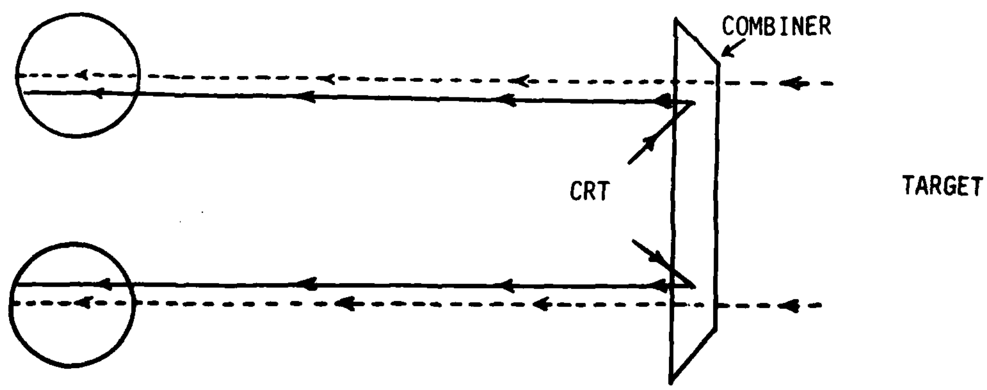

Figure 2B. The HUD combiner affects light from both the target and the CRT. (top view)

AD-P003 160

SUN/MOON CAPTURE EVALUATION

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INTRODUCTION.

Because of their optical characteristics, head-up displays (HUDs) have always interacted with various kinds of sunlight to produce unwanted reflections.

"Capture" means that a HUD can and will capture or trap light and direct it into a pilot's eyes. This capture effect can result in both reflections and retroflections. Reflections occur when an external light source impinges on a reflective surface. Retroflections are light reflections that result from external light entering the HUD optics train, reflecting off the face of the cathode ray tube (CRT), and passing back out through the optics. Both the reflected and the retroflected image are called reflexes.

With the introduction of diffractive optics technology, there is a need to describe how diffraction and conventional optics perform in the presence of collimated light sources, such as that provided by the sun and moon.

EVALUATION OF CAPTURE CHARACTERISTICS.

The capture evaluation was intended to determine the susceptibilities of conventional and diffractive HUDs to external light sources. Two different conventional HUDs and one diffractive HUD were evaluated. The test setup in Figure 1 provided a means of moving a collimated fiber optic (artificial) sun through a constant arc in front of, behind, and to either side of the HUD.

A string was tied to a point at mid combiner and used to provide a constant distance for the fiber optic light source. A video camera was positioned at the design eye location to look through the HUD combiner at an eye chart as the artificial sun was moved. The angle between the video camera and the HUD combiner was adjusted to duplicate the A/C installation.

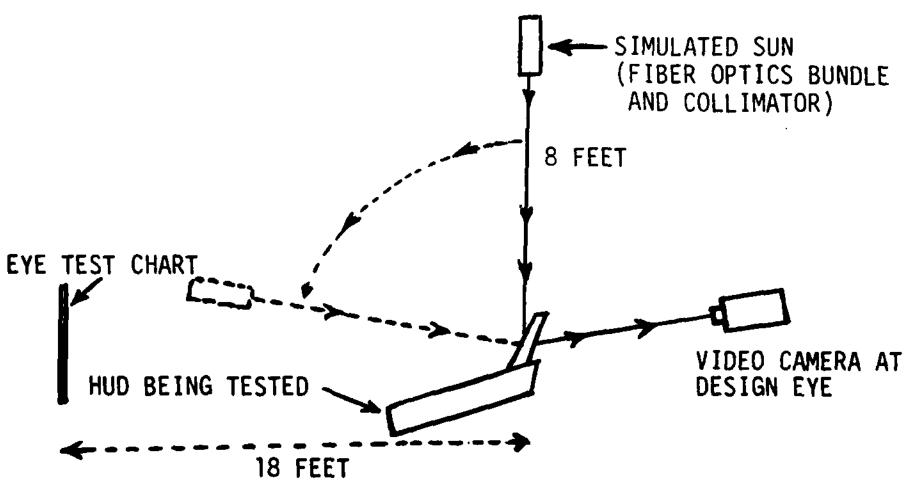
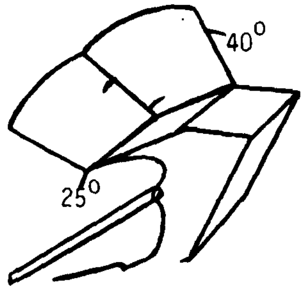
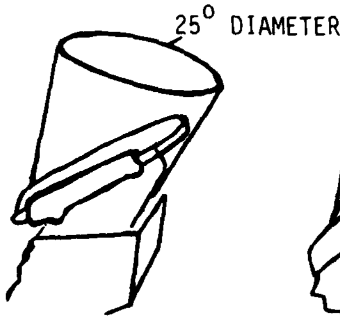


Fig. 1. Lab set up for measuring HUD capture characteristics.





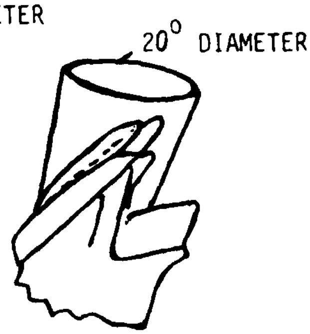


Fig. 1 Diffraction HUD Fig. 2 Conventional HUD A Fig. 3 Conventional HUD B

Ray trace drawings provided by the vendor for the diffraction HUD and the two conventional HUDs (Figures 2,3,4,) indicated that there should be cone or wedge shaped solid angles above the HUDs where light can enter and be visible to the pilot.

Measurements (Figure 5) of these solid angles indicated that they were approximately half the size of those predicted by the HUD vendor. A possible secondary cone was found with the diffractive HUD that appears to be oriented much more forward than the primary or main cone. The importance of this secondary cone is questionable, however, since the reflex brightness for a small sample was quite low.

The reflex areas were measured and appear in Figure 5. Looking at the sun/moon spot data within this figure, one can see that light entering the diffractive HUD main cone results in a much smaller area than for the conventional HUDs evaluated. Reflective reflex area increased when the diffractive HUDs secondary cone was exercised. The secondary cone could not be fully evaluated due to time constraints. Its size and shape is uncertain, but some of its characteristics are plotted (Figure 6) against light source elevation and reflective reflex area at constant azimuth angles.

A substantial peak occurs at 7.2 degrees elevation and 18.6 degrees left of HUD center in Figure 6. A large percentage of this peak results from an apparent haze having low brightness compared to the brightness of other reflex areas. The transmittance of a representative reflective reflex area was .00559 percent for haze and .00434 percent for a spot. A conventional HUD's retroflective reflex transmittance ranged from .0121 percent to .63 percent.

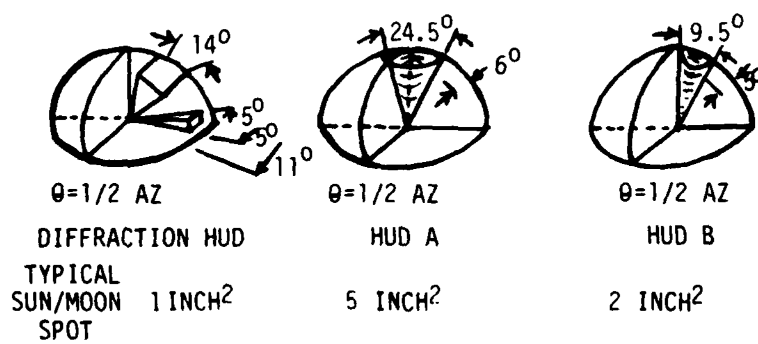


Figure 5. Capture Characteristics

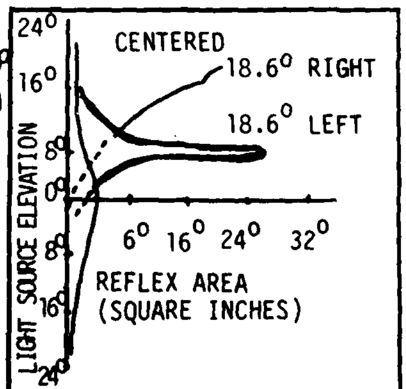


Fig. 6. Reflections outside primary capture cone.

Another limitation was with respect to how closely we could simulate the sun and its interaction with the atmosphere. On the one hand, a cloudless haze-free sky permits a more-or-less collimated sun. As the optical characteristics of the atmosphere changes with increases of dust and or moisture, the collimation of the sunlight is disrupted.

In our evaluation, a sort of reciprocity was found when two light sources having different collimation characteristics were used. In general, the diffraction HUD defocussed the reflex image produced by the more collimated light source at the design eye position. More uncollimated light from the other source was focussed at the design eye position by the diffraction HUD.

Additional data needs to be generated to more accurately measure the secondary cone characteristics and to evaluate these sun and moon image susceptibilities in terms of their impact on pilot contrast sensitivity losses.

ESTIMATING DETECTION RANGE AND RANGE LOSS LOOKING THROUGH WINDSHIELDS AND HEAD-UP DISPLAYS

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It is very important for an aircraft pilot to be able to detect distant objects. His ability to do so is impaired by loss of target contrast due to the atmosphere and to passive optical elements through which he must look. These elements are the aircraft's windshield and head-up display (HUD) and his own helmet visor and spectacles or sun glasses. The problem is to determine loss of target detection range due to loss of contrast. This report examines loss of detection range by combining sighting geometry with the contrast transmission of the atmosphere and other optical elements and with human ability to detect targets. Numerical examples will be presented as tutorial exercises and target detection ranges for selected conditions will be worked out in detail to familiarize the reader with the graphical method derived in this paper.

The visibility of a uniform round disc-shaped target depends upon its apparent contrast, its angular subtense, and the background luminance. Blackwell (1946) collected extensive data on threshold visibility as a function of the contrast, angular subtense and luminance of circular discs. Duntley (1948) used Blackwell's data to construct nine nomograms or visibility charts for finding detection distance for a wide range of meteorological range (a measure of visibility through the atmosphere) and target area. Each nomogram covered a different value of background luminance. The nomograms were constructed to avoid tedious solution of detection range by a series of successive approximations.

Middleton (1952) modified these nomograms to portray ranges at which detection probability was .95 rather than .50, the detection threshold. The Duntley-Middleton nomograms are adequate for some purposes, especially when it is not necessary to interpolate. However, a method for determining target detection range without using nomograms permits flexibility in examining the effects of contrast and contrast losses due to the atmosphere and to optical devices through which the pilot must look. For this reason, the following paragraphs will develop such a method. This method is a graphic one.

(A) METEOROLOGICAL RANGE AND ATMOSPHERIC APPEARANCE

Meteorological range V, sometimes designated as R_V and sometimes called visibiity range or visibility, is a measure of atmospheric clarity or contrast attenuation. The clearer the air the greater the meteorological range. Although visually given in thousands of yards in the USA, countries on the metric system of measurements state it in kilometers. The appearance of the atmosphere in terms of how it would be described correlates with V. The relationship between appearance and V is shown in Table 1 which is derived from Middleton (1953). Since most Americans visualize long distances in miles more readily than in kilometers or thousands of yards, the table also has a miles column.

TABLE 1
ATMOSPHERIC DESCRIPTION AND METEOROLOGICAL RANGE (V)

APPEARANCE	KILOMETERS	THOUSANDS OF YARDS	MILES
Moderate fog	.35 - .5	.38 - .54	.2 - .3
Light fog	.5 - 1	.54 - 1.1	.3 - .6
Thin fog	1 - 2	1.1 - 2.2	.6 - 1.2
Haze	2 - 4	2.2 - 4.4	1.2 - 2.5
Light Haze	4 - 10	4.4 - 11	2.5 - 6.2
Clear	10 - 20	11 - 22	6.2 - 12
Very Clear	20 - 50	22 - 55	12 - 31
Exceptionally Clear	50+	55+	31+

Thousands of Yards = (1.093) (Kilometers)
Miles = (.6214) (Kilometers)
Meteorological range V is sometimes called R_V.

The Air Force can seldom fly its missions in a very clear atmosphere, for it is rather infrequent. Thus, according to Table 1, V will usually be less than 12 miles or 22,000 yards. Many locales very seldom have even 10-mile visibility. Most operations probably take place in the range of 2.5 - 10 miles or 4,400 - 17,600 yards. Two of the examples in the present paper are worked out for a meteorological range V of 9,000 yards (light haze) and one for a V of 13,000 yards (clear).

(B) DERIVATION OF METHOD

The contrast of a distant object is reduced or attenuated by the intervening atmosphere. That is, an object having an inherent contrast C_o with the sky at zero range (R=0) is reduced in contrast at range R to C_R according to the atmospheric contrast attenuation formula $C_R=C_o \text{ EXP}(-\sigma R)$, where σ is the beam attenuation coefficient, and EXP is e = 2.718 (which is the base of natural or Naperian logarithms) to the given power or exponent, here $-\sigma R$.

Duntley (1946) defined a quantity V as meteorological range, or the range at which the contrast transmittance of the atmosphere is two percent, i.e., $C_R/C_o=.02=e^{-\sigma V}$. Inverting both sides of this equation yields $1/.02=50=e^{\sigma V}$. Taking natural logarithms of both sides yields $\text{Log}_e(50)=3.912=\sigma V$, from which $\sigma=3.912/V$. Replacing σ in the original equation for contrast attenuation by the atmosphere with this value of σ yields the basic contrast attenuation formula in terms of meteorological range, $C_R=C_o \text{ EXP}(-3.912R/V)$. From this formula $C_R/C_o=\text{EXP }(-3.912R/V)$. Taking natural logarithms of both sides of this equation yields $L_N(C_o/C_R)=3.912R/V$, where $L_N=\text{Log}_e$. Solving this for R yields

$$R = (V/3.912)L_N(C_o/C_R) \text{ yards}, \quad \text{V in yards} \qquad \text{EQN (1)}$$

As a matter of interest, Middleton (1952) mentions that possibly $C_R/C_o = .02$ is a bit low, and that there might be some value in redefining this to be .05 instead of .02. This would replace the constant 3.916 with $L_N(20)=2.996$, and the meteorlogical range V would be a different quantity. Since Middleton's worthwhile suggestion has not been followed, it will not be pursued further in this paper.

Equation (1) defines R in terms of inherent contrast, apparent contrast and meteorological range. It is based on atmospheric contrast transmission. It is also possible to find a value of R based on the size and distance of the target. At a range R, a target with a diameter D subtends, at the observer's eye, an angle α. As shown in Figure 1, the tangent of the half angle is given by $TAN(\alpha/2) = (D/2)/R$. For a small angle, the tangent of the angle is equal to the angle in radians. Thus, $TAN(\alpha/2) = (\alpha/2 \text{ minutes})/3438$, from which $(\alpha/2)/3438 = D/2R$, or $R=3438D/\alpha$. If the target is a round disc, its area is $A=\pi D^2/4 = .7854D^2$, from which $D=\sqrt{A/.7854}=\sqrt{A}/.8862$. Since meteorological range V is usually given in yards while target area A is usually in square feet, this value of D must be divided by 3 to obtain detection range R in yards. This division yields D yards$=(\sqrt{A})/(.8862)(3) = (\sqrt{A})/2.6587$. Inserting this value of D in the formula $R=3438D/\alpha$ gives $R=(3438\sqrt{A})/2.6587$, which reduces to

$$R = (1293\sqrt{A})/\alpha \text{ yards} \qquad \text{EQN (2)}$$

A in Ft.^{2}, α in minutes of arc

The value of R from Equation (1) may be equated to the value of R given by Equation (2), yielding $(V/3.912)L_N(C_o/C_R)=(1293\sqrt{A})/\alpha$. This reduces to

$$L_N(C_o/C_R)=(5058\sqrt{A})/\alpha V \qquad \text{EQN (3)}$$

A in Ft.^{2}, α in minutes of arc,
V in yards

In addition to the loss of contrast due to scattering of light by the atmosphere, any optical element in the path between the observer and the target will cause a further loss of brightness contrast. Whenever light passes through a substance, some light is scattered within the material. This is especially true for clear plastics. Whenever light encounters a change in refractive index, some light is scattered. Optical coatings, especially the highly efficient multilayer antireflection coatings, reduce reflections, hence cut down on light that produces reflections and veiling luminance which reduce contrast. However, no coating eliminates all contrast loss. Thus, the aircraft windscreen, the head-up display (HUD), the pilot's visor and spectacles or sunglasses, if worn, all act to reduce contrast.

Let the letter K_J denote the contrast loss due to optical device j, then $1-K_J$ is the contrast transmission C_R/C_o, i.e., $1-K_J= C_R/C_o$, or $C_R=(1-K_J)C_o = (1-K_J)C_o\text{Exp}(-3.912R/V)$. Thus, by replacing C_o by $(1-K_J)C_o$ in the basic equation(3) the equation then takes into account the contrast loss due to the optical element j. When there are several optical elements in series, such as an aircraft windscreen, head-up display and the pilot's visor and sunglasses or spectacles, the contrast transmissions are multiplicative. In this case, C_o is replaced by $(1-K_1)(1-K_2)(1-K_3)(1-K_4)C_o$, the subscripts denoting successive optical devices or elements. The general equation, in the case where a series of optical elements add their contrast losses to that caused by the atmosphere, is then

$$(5058\sqrt{A})/\alpha V = \text{Log}_e[(1-K_1)(1-K_2)(1-K_3)(1-K_4)C_o/C_R] \qquad \text{EQN (4)}$$

A in Ft.^{2}, α in minutes of arc, V in yards

Examination of Equations (3) and (4) reveals that they each contain two unknowns, α and C_R. However, these two unknowns or variables are not independent variables. For any particular value of C_R, there is a corresponding or matched value of α, which is the smallest angular subtense at which the target is detectable with a given probability. Clearly, larger angles or higher contrasts are required when scene illumination is lower, available time is less or higher detection probabilities are desired. In any case, the matching values of C_R and α are obtained from human factors data in the scientific literature on target detection. An example is provided by Table 2, which is for a light level or sky luminance of 1,000 millilamberts. The paired values are for 15-second observer look times from Blackwell's research (1946).

TABLE 2
ANGULAR SUBTENSE REQUIRED FOR DETECTION AT VARIOUS APPARENT CONTRASTS AT 1,000 MILLILAMBERTS

α	35.4	4.86	5.01	2.54	1.90	1.30	.743	.375
C_R	.001	.005	.01	.03	.05	.1	.3	1
$C'_R=2C_R$	.002	.01	.01	.06	.1	.2	.6	2

NOTE: The above is for an available look time of up to 15 seconds. C_R is for detection probability of .5, $C'_R=2C_R$ is for P=.95.

Blackwell's original data was for threshold detection, which is defined as a detection probability of .5. To convert these values for a .95 probability, according to Blackwell, one multiplies contrast by 2. This is done on the third line of the table, where $C'_R=2C_R$ is listed.

To use Equations (3) or (4), note that the value of α at detection is the one that makes the two sides of the equation equal. To find α graphically, one side of the equation is plotted against the other. The point where this curve intersects a line representing equal values of the two axes of the graph (or equality of the two sides of the equation) is the point of interest. It yields the value of $(5058\alpha\sqrt{A})/V$ from which α is calculated. With α now known, R is calculated from Equation (2). In the following paragraphs examples will be given for specified conditions and target detection ranges will be solved for them. Examples increase in complexity from the first through the last one.

(C) Example with contrast loss due only to the atmosphere.

To illustrate graphical solution for detection range, the first example is for contrast loss due only to the atmosphere (the losses due to windscreen, HUD, visor, and spectacles are ignored or postponed for a later example). Since this paper is a tutorial, considerable computational details will be given, thus assisting readers not proficient with logarithms or exponentials. For this first example, suppose that target area A is 100 Ft.^{2}, inherent target contrast against the horizon sky C_o is 1, meteorological range V is 9,000 yards, corresponding to a light haze or almost clear, and that the target is to be detected with a sky background of 1,000 millilamberts. Suppose that target detection probability is to be .95, not the .5 of threshold detection. The problem is to find target detection range, R.

Inserting the values of A, C_O and V into Equation (3) yields Ln $(1/\dot{C}_R) = (5058\sqrt{100})/9{,}000\alpha$. This equation reduces to $\text{Ln}(1/\dot{C}_R) = 5.62/\alpha$. Using Table 2 paired values of α and C_R and this equation permits calculation of corresponding values of $\text{Ln}(1/C'_R)$ and $5.62/\alpha$. Paired values of these two quantities are given in Table 3.

TABLE 3

MATCHING* VALUES OF α AND $\dot{C}_R$ AND MATCHING VALUES OF LN($1/\dot{C}_R$) AND $5.62/\alpha$

	35.4	8.60	5.01	2.54	1.90	1.30	.743	.375
$C_R=2C_R$	.002	.01	.02	.06	.1	.2	.6	2
LN($1/C_R$)	6.21	4.61	3.91	2.81	2.30	1.61	.511	-.693
5.62/	.159	.653	1.12	2.21	2.96	4.32	7.56	15.0

*For 1,000 Millilamberts and up to 15 seconds viewing time.

The value of α that represents the angular subtense of the target at maximum detection range is the value of α at which LN($1/\dot{C}_R$) is equal to $5.62/\alpha$. In the table, note that these two quantities are presented in matching pairs on the bottom two lines. Inspection of Table 3 reveals that α (on the top line) lies between 1.90 and 2.54. This is apparent because, at $\alpha=2.54$, LN($1/C_R$) is larger than $5.62/\alpha$, whereas at $\alpha=1.90$ it is smaller.

To find the value of α, it is necessary to plot LN($1/\dot{C}_R$) against $5.62/\alpha$. This is done on Log-Log paper in Figure 2, yielding a curved line for the connected data points. An "equality" line is then plotted, connecting all points where the two axes of the graph have the same value. On log-log graph paper this is a straight line. The point of interest on the graph is the point of intersection of the two lines. In Figure 2, the value of $5.62/\alpha$ at the point of intersection of the two lines is 2.56, from which $\alpha=5.62/2.56 = 2.195$. Using this value of α in Equation (2) yields $R=(1293\sqrt{100})/2.195 = 5{,}891$. Thus, maximum target detection range is R=5,890 yards for the first example with contrast loss due only to the atmosphere. As a matter of interest, at the intersection point of the two lines, LN($1/\dot{C}_R$) is also 2.56, from which $1/\dot{C}_R = e^{2.56} = 12.93$. Thus $\dot{C}_R=1/12.93 = .077$. At detection, then, the apparent target contrast is .077, about 1/13th of the inherent target contrast of 1.

The line of equality used in this example was plotted from values on the two axes of the graph; not from situation geometry, the atmospheric contrast attenuation and human factors data. Thus, it may be plotted with great precision, since one has an infinite number of available points to connect. Because of the vast number of available points, for precise plotting the equality line need not be a straight line, and on a semi-log plot, where one axis, Log ($Q/\dot{C}_R$)

is logarithmic and the other axis, $5.62/\alpha$, is linear, the equality line is not a straight line. In contrast to the vast number of zero-spaced points in the equality line, the plot of the equation has only a very few data points. When these points fall on a straight or nearly straight line, plotting accuracy is increased. Accordingly, Figure 3 is a plot of the data points of Table 2 on semi-log graph paper, where one axis is linear and the other is logarithmic. On the logarithmic or vertical axis note that, for example, the space between 1.5 and 2 is larger than that between 3.5 and 4. Since, on the available graph paper the log axis is vertical, $LN(1/\dot{C}_R)$ is plotted on the vertical axis, instead of the horizontal axis as it was in Figure 2.

As anticipated, the data points from Table 2 now come quite close to falling on a straight line. The data points are easily and accurately connected. On this graph, at the intersection point of the lines, $5.62/\alpha$ is 2.55, so that α=2.204 and $R=(1293\sqrt{100})/2.204$ = 5,887. Thus, as before in Figure 2, target detection range is 5,890 yards.

(D) AN EXAMPLE WITH VARIOUS HUD CONTRAST LOSSES

The first example was for atmospheric contrast loss only; the windscreen, the HUD and pilot's visor and sunglasses were ignored. In this second example, both atmosphere and HUD will be taken into account, but not windshield, visor or spectacles.

Assume, as before, that A=100 and V=9,000. However, let inherent target contrast now be $\dot{C}$=.5, not 1 as before, and let HUD contrast losses be 0, 10% and 20%. Inserting these values of A and V into the left side of Equation (4) yields $(5058\sqrt{100})/9{,}000\alpha = 5.623/\alpha$, as before. The left side becomes, for the three values of K, $Log_e[(1-0)(.5)/\dot{C}_R]$, $Log_e[(1-.1)(.5)/\dot{C}_R]$ and $Log_e[(1-.2)(.5)/\dot{C}_R]$, i.e., $LN(.5/\dot{C}_R)$, $LN(.45/\dot{C}_R)$ and $LN(.4/\dot{C}_R)$, respectively, for increasing HUD contrast loss. The three equations, used with the Data in Table 1 for matching values of α and $\dot{C}_R$, yield Table 4. The data in this table are plotted on linear-linear graph paper in Figure 4, with data points connected with hand-drawn curved lines. The data are plotted on semi-log (or linear-log) graph paper in Figure 5, with almost straight lines connecting data points. Note that drawing in the lines appears to be (and is) a simpler task for the second graph.

The inserted tables on the graphs list target detection ranges and percent loss of detection ranges for the K values of the HUD's. Differences in detection ranges are minuscule between the two graphs, the maximum difference being for K=.1. Here, it is only (4850-4820)(100)/4850 = .6%. Note that a 10% loss in target contrast attributable to the HUD results in a loss in detection range of only about 2.5%, while a 20% HUD loss produces only about a 5.5% loss in range. This latter is for a HUD that produces so much contrast loss as to be labeled "bad" on the graph, but range loss is still very small.

TABLE 4
EQUATIONS FOR HUD CONTRAST LOSSES OF 0, 10, AND 20%

			K=0 1-K=1	K=.1 1-K=.9	K=.2 1-K=.8
α	$5.620/\alpha$	$\dot{C}_R$	$LN(.5/\dot{C}_R)$	$LN(.45/\dot{C}_R)$	$LN(.4/\dot{C}_R)$
35.4	.159	.002	5.521	5.416	5.298
8.6	.653	.01	3.912	3.807	3.689
5.01	1.122	.02	3.219	3.114	2.996
2.54	2.213	.06	2.120	2.015	1.897
1.90	2.958	.1	1.609	1.504	1.386
1.30	4.323	.2	.916	.811	.693
.743	7.564	.6	-.182	-.288	-.405
.375	14.987	2			

(E) AN EXAMPLE WITH ATMOSPHERE, WINDSHIELD HUD, AND SPECTACLES

In an aircraft the pilot must look through the atmosphere, the aircraft windshield and, usually, the head-up display. He may also be wearing a helmet visor and/or spectacles. Each of these causes loss of target contrast, hence, detection range. This final example will illustrate the case where such optical devices are in series, the case covered by Equation (4).

For this example, assume that the target is a uniform circular disc with an area of A=150 Ft.^{2}, with an inherent target contrast against the horizon sky of C_o=.5, and that the sky luminance is 1,000 millilamberts. Let the aircraft windshield be a good one, as windscreen contrast transmission goes, having a contrast transmission of .95 (or K=.05), and let the pilot wear clean unscratched clear spectacles with a contrast transmission of.98. Let the meteorological range be 13,000 yards or about 7.4 statute miles. This lies in the clear air range of 11-22 thousand yards, between the light haze and the very clear visibility ranges. For this problem, let the desired probability of target detection be .95, not the .5 of threshold detectability. The problem is to find target detection range for these conditions when the pilot is looking through HUDS that cause target contrast losses of 3 (good), 8 (not good), 12 (bad), 16 and 20% (extremely bad). In addition, the relative target detection ranges are to be discussed.

For the K=.03 HUD and the above listed initial conditions (.95 contrast transmission windshield, .98 spectacles), inserting A, V and C_o into Equation 4 yields: $(5058\sqrt{150})(13,000\alpha) = \mathrm{Log}_e[(1-.05)(1-.03)(1-.02(.5)/\dot{C}_R]$. This reduces to $4.77/\alpha = \mathrm{Log}_e\,(.452/\dot{C}_R)$. This equation, and the equations for the various other HUD conditions of the example, calculated in a similar way, are listed in Table 5 below.

TABLE 5
EQUATIONS FOR VARIOUS ASSUMED CONDITIONS

ASSUMED CONDITION	RESULTANT EQUATION
AIR ONLY, NO OPTICS	$4.77/\alpha = \mathrm{Ln}(.5/\dot{C}_R)$
Windscreen* & Spectacles*	
HUD K=0	$4.77/\alpha = \mathrm{LN}(.466/\dot{C}_R)$
HUD K=.03	$4.77/\alpha = \mathrm{LN}\ (.452/\dot{C}_R)$
HUD K=.08	$4.77/\alpha = \mathrm{LN}\ (.428/\dot{C}_R)$
HUD K=.12	$4.77/\alpha = \mathrm{LN}\ (.410/\dot{C}_R)$
HUD K=.16	$4.77/\alpha = \mathrm{LN}\ (.391/\dot{C}_R)$
HUD K=.20	$4.77/\alpha = \mathrm{LN}\ (.372/\dot{C}_R)$

* Canopy K=.05, Spectacle K=.02

To plot the 7 equations of Table 5 requires matching values of α and $\dot{C}_R$, which are listed in Table 2. The calculated values given in Table 6 permit plotting all of the equations, namely the matching or paired values of $4.77/\alpha$ and LN $(Q/\dot{C}_R)$, where Q has values of .5, etc.

TABLE 6
DATA POINTS FOR PLOTTING EQUATIONS

$4.77/\alpha$	35.4 .135	8.60 .555	5.01 .952	2.54 1.88	1.90 2.51	1.30 3.67	.743 .642
$\dot{C}_R = 2C_R$	.002	.01	.02	.06	.1	.2	.6
$\mathrm{LN}(.500/\dot{C}_R)$	5.52	3.91	3.22	2.12	1.60	.916	-.182
$\mathrm{LN}(.466/\dot{C}_R)$	5.45	3.84	3.15	2.05	1.54	.846	-.253
$\mathrm{LN}(.452/\dot{C}_R)$	5.42	3.81	3.12	2.02	1.51	.815	-.283
$\mathrm{LN}(.428/\dot{C}_R)$	5.37	3.76	3.06	1.96	1.45	.761	-.338
$\mathrm{LN}(.410/\dot{C}_R)$	5.32	3.71	3.02	1.92	1.41	.718	-.381
$\mathrm{LN}(.391/\dot{C}_R)$	5.28	3.67	2.97	1.87	1.36	.670	-.428
$\mathrm{LN}(.372/\dot{C}_R)$	5.23	3.62	2.92	1.82	1.31	.621	-.478

Note the dark vertical lines that separate values between which the intersection points lie, indicated by $4.77/\alpha$ changing from less than $\mathrm{LN}(Q/\dot{C}_R)$ to more than $\mathrm{LN}(Q/\dot{C}_R)$, where Q=.428, etc.

As noted and shown earlier, using semi-log (or log-linear) graph paper yields data curves that are much straighter, and thus easier to draw. Some readers may wish to plot the data as a tutorial exercise, but may not have suitable semi-log graph paper, so must plot it on ordinary (or linear-linear) graph paper. For this reason, the data is shown plotted on ordinary graph paper in Figure 6. The semi-log plotting will be discussed later.

To obtain adequate precision in plotting the data and in reading out values of $4.77/\alpha$ at the curve intersection points, Figure 6 uses 50 graph lines or divisions for each unit on each axis. For example, there are 50 divisions or lines between $4.77/\alpha=1$ and $4.77/\alpha=2$. One value of $LN(.5/C_R)$ to be plotted from the table is 3.22. This is plotted at (.22)(50)=11.0 lines or divisions past 3.0 on the graph.

All plotted data points were connected by smooth hand-drawn curves. After reading out values of $4.77/\alpha$ at the intersection points, the lines were darkened, for graph reproduction purposes, with a ballpoint pen. Table 7 provides the plotting values of $4.77/\alpha$ and values of this quantity at the intersection points of the data curves and the line of equal axis values. The target detection ranges and the loss in detection range for each value of K are given in Table 8. Figure 7 plots detection range as a function of K, while Figure 8 plots detection range loss for each K value.

TABLE 7

PLOTTING AND READOUT DATA FOR LINEAR PLOT

(A) PLOTTING VALUES* OF $4.77/\alpha$

$4.77/\alpha$	Plotting Position on Graph
.555	.5+.055x50 = .5+2.8 lines**
.952	.9+.052x50 = .9+2.6 lines
1.88	1.5+.38x50 = 1.88+19.0 lines
2.51	2.5+.01x50 = 2.51+.5 lines
3.67	3.5+.17x50 = 3.67+8.5 lines

*Corresponding values of $LN(Q/C_R)$ are worked out in similar fashion.

**Lines or divisions on the graph paper.

(B) READING OUT $4.77/\alpha$ VALUES AT CURVE INTERSECTION POINTS

CURVE	VALUE OF $4.77/\alpha$
A	1.5 + 17.4*/50 = 1.848
B	1.5 + 18.8/50 = 1.876
C	1.5 + 19.9/50 = 1.898
D	1.5 + 21.0/50 = 1.920
E	1.5 + 22.7/50 = 1.954
F	1.5 + 23.5/50 = 1.970
G	2.0 + 0/50 = 2.000

*17.4 lines or divisions on graph paper above 1.5, etc.

TABLE 8
DETECTION RANGES AND RANGE LOSS DUE TO CONTRAST LOSS

CONDITION	$4.77/\alpha$	α	DETECTION RANGE, YDS**	% OF RANGE LOSS++ RELATIVE TO: ALL OPTICS, & K=0	% OF RANGE LOSS++ RELATIVE TO: NO OPTICS
G (Air Only, No Optics*	2.000+	2.385	6640		0
Air, HUD, Windshield, Spectacles; HUD K of:					
F 0	1.970	2.421	6,540	0%	1.5%
E .03	1.954	2.441	6,490	.8%	2.3%
D .08	1.920	2.484	6,380	2.4%	3.9%
C .12	1.898	2.513	6,300	3.7%	5.1%
B .16	1.876	2.583	6,230	4.7%	6.2%
A .20	1.848	2.581	6,140	6.1%	2.5%

* No optics = no canopy, no HUD, no spectacles.

** $R=(1293\sqrt{A})/\alpha \approx (1293\sqrt{150})/\alpha = 15{,}836/\alpha$ Yards. Ranges are rounded off to three significant digits.

\+ This is from $4.77/\alpha = 2+(.3 \text{ line}/50 \text{ lines})$ at intersection = 2.006. Other values of $4.77/\alpha$ are similarly calculated.

++ Loss relative to all optics, K=0, is loss relative to a perfect no loss HUD, but with windshield and spectacles, while loss relative to no optics is loss relative to no windshield, HUD or spectacles. Formulas used are:

R loss, all optics = [(R for K=0)-(R for used K)]x100/(R for k=0);
R loss, no optics = [(R air only)-R for K used (with windshield, spectacles)]x100/(R air only)

+++ Windshield contrast loss = 5%, spectacle contrast loss = 2%.

From inspection of Table 8, and from the plot of detection range loss as a function of contrast loss of Figure 8, it is apparent that the loss of target detection range is much smaller than the loss of contrast when both losses are expressed as percentages. For example, a HUD with a target contrast loss of 8%, which is considerable for a HUD, would, under the conditions of the example, cause a loss of target detection range when looking through the atmosphere only (no windscreen or spectacles), of about 4%.

Semi-log plots for target detection range determination, as noted, are preferable to plain graph paper plots. The data of Table 6 for atmosphere, windshield, HUD and spectacles are thus plotted on semi-log paper in Figure 9. This graph uses 40 lines or divisions per unit on the linear vertical axis, i.e., on the $4.77/\alpha$ axis. Table 9 gives plotting information, curve intersections and detection ranges for this graph. The target detection ranges, as expected, come out very close to those obtained with the linear graph, as may be noted from Table 10 which compares the two. Note that, rounded to 3 significant digits, 4 of the 7 comparisons show no difference and 3 differ by less than 1/2%. With repeated replotting, minute differences are to be expected, whether using semi-log or linear graph paper. The graphic method is not exact, but departure from exactness is trivial when graphs are carefully made.

TABLE 9

ATMOSPHERE + WINDSHIELD + HUD + SPECTACLES; SEMI-LOG GRAPH: PLOTTING, CURVE INTERSECTIONS AND DETECTION RANGES

(A) Plotting on 4.77/ vertical axis on semi-log paper

1 unit	=	40 vertical divisions or lines.
.952	=	.9+.052x40=.9+2.1 lines
1.88	=	1.8+.08x40=1.8+3.2 lines
2.51	=	2.5+.01x40=2.5+.4 line

(B) Curve intersection points and detection ranges

VERTICAL AXIS

	HUD K	4.77/α	α	R=15,836/α
A	.20	1.8+2.0/40 ** = 1.850	2.578	6143=6,140 *** Ft.
B	.16	1.8+3.0/40 = 1.875	2.544	6200=6,200
C	.12	1.8+3.9/40 = 1.898	2.513	6302=6,300
D	.08	1.9+.85/40 = 1.921	2.483	6378=6,380
E	.03	1.9+2.2/40 = 1.955	2.440	6490=6,490
F	.0	1.9+2.9/40 = 1.972	2.419	6547=6,670
G	.0	2.0+.3/40 = 2.008	2.375	6668=6,670

* Read using ruler graduated in 1/100th inch and a magnifier.

** 1.8+(2.0 lines)/(40 lines per unit) = 1.850

*** Rounded to 3 significant digits

TABLE 10

DETECTION RANGE COMPARISON: SEMI-LOG VS. LINEAR GRAPHS

GRAPH	CONDITION						
	G	F	E	D	C	B	A
M=Semi-Log	6670	6550	6490	6380	6300	6200	6140
N=Linear	6640	6540	6490	6380	6300	6230	6140
M-N	+30	+10	0	0	0	-30	0
% Difference	+.45%	+.15%	0	0	0	-.48%	0

% Difference = (100)(M-N)/M

NOTE: The largest % difference is less than 1/2%, i.e., is trivial.

(F) RANGE DETERMINATION FROM LABORATORY DATA

The detectability of a target depends upon the target and its behavior, the environment, the aircraft windscreen and head-up display, and upon the pilot and his behavior. Taylor (1964) discusses the use of visual performance data in visibility prediction as does Duntley (1964). The reader may find Duntley's earlier paper (1946) to be of some interest. However, none of these references mention graphic methods nor do any of them cover the material that is discussed in the following paragraphs.

In the examples used in the present paper, detection range was determined for stationary circular targets having uniform lightness appearing on a uniform sky background with a luminance of 1,000 millilamberts. Calculations and graphs were based on Blackwell's 1946 laboratory data collected from observers who were allowed up to 15 seconds to look at a fixed point in space where they knew the target was located if it was present. No search was involved, nor was there present any annoyances or distractions, vibration and noise, reduced partial oxygen pressure, etc., that would reduce performance.

In military situations, the observer usually does not know where the target will appear and knows that at any particular time a target is probably not present. In contrast to the laboratory observer, he does not stare at a fixed location. Instead, he searches the scene, devoting very little time to any one point in space. When such search behavior is involved, data for pair values of apparent contrast and angular target subtense for only short glimpse times may be used, such as the data of Taylor (1964). With short glimpses, human contrast sensitivity is less than when long looks are possible, hence target detection ranges are shorter. If the range to the target is decreasing, the target may well not be seen until quite close; the pilot will be thinking about something else and be looking somewhere else.

The laboratory data used in the examples has other limitations. For example, pilots must often divide attention between cockpit instruments at close range and the distant scene. Any look from one to the other requires refocussing of the eyes, which takes a little time. When looking out, the lack of visible details can cause an improper near focus which occurs under empty field conditions, even with long viewing time, a condition called empty field myopia (nearsightedness). This focus error appreciably reduces contrast sensitivity. Also, looking from a relatively dark instrument panel to a bright sky may involve a luminance adaptation level mismatch for the observer, further reducing contrast sensitivity.

In an aircraft windshield and head-up display, there can be reflections, single and multiple, from the sun, bright sunlit clouds and aircraft instruments. In some aircraft orientations with respect to the sun, the HUD may produce bright spots and halos. In some head-up displays, there are noticeable reflections from the pilot and his clothes and even from the checklist on his lap. Sometimes reflections are so dim as to be unnoticed or even not visible, but they may still act as veiling luminances that reduce the apparent contrast of the target. Even when reflections and glare sources fall to one side of the target image, thus not reducing its contrast, they may reduce the observer's contrast sensitivity. In addition, by serving as a source of annoyance and distraction, reflections and bright spots may effectively reduce target detection range.

Aircraft vibration, reflections and glare, reduced oxygen pressure, empty field myopia, inside-outside eye refocussing and luminance adaptation level mismatch all reduce contrast sensitivity, hence reduce maximum possible target detection range. When the distance to the target is decreasing, as it often is, imperfect attention and concentration, the press of other tasks, etc., in combination with search behavior act to reduce target detection range even below the distance that atmosphere and optics would permit. In theory as well as practice, pilots, as already noted, do not detect targets when their size and contrast place them at or slightly above visibility. Usually, when a target is first noticed it is already much closer than simple theory might predict and may be close enough to even be recognized. Because detection seldom takes place at near detectability distance, the actual loss in target detection range attributable to the windscreen and HUD may be appreciably less than that found in the examples worked out in this paper.

The laboratory data that were used in the examples worked out in detail for the present paper were mean or average values. The variability or scatter of the laboratory data, as indicated by the standard deviations, was not used. Thus, the examples arrived at average values for target detection range. That was their intention. However, it is very likely that some of the observers had appreciably higher sensitivity to contrast than did others, even though all had normal or 20/20 visual acuity as measured by conventional eye charts of the letter type. Recent evaluations of contrast sensitivity by Ginsburg (1981), using sine wave gratings, have found large differences in contrast sensitivity between aircraft pilots in some parts of the spatial frequency spectrum, even though they also had normal visual acuity as measured by conventional eye chart tests. In human abilities, large differences between individuals are to be expected.

Since the basic method for finding target detection range in the present paper is based on the use of paired values of α and C_R, it is applicable to low, average or high contrast sensitivity individuals, provided only that the data is available or can be calculated from means and standard deviations reported in the scientific literature. Hence, it was not deemed necessary to complicate the tutorial examples of this paper by working out additional target detection ranges to illustrate the effects of individual differences in contrast sensitivity.

(G) SUMMARY

The present paper is a tutorial on determining target detection range by a graphic method. It was worked out and presented because of the inadequacy of available methods. The method of successive approximations used many years ago was time consuming and tedious in application. Duntley (1948) worked out a nomographic method to avoid successive approximations. However, using nomograms presents problems due to the small size of available nomograms. This makes them difficult to read accurately, especially when interpolation for target size, meterological range or inherent target contrast is involved. Nomograms also lack flexibility and their use gives little insight into the target detection process.

The method for determining target detection range worked out for this paper involves construction of a graph. Using the atmospheric contrast transmission formula and the size-distance geometry of the target, a formula was derived. It contains only two unknowns, angular subtense α of the target at detection and apparent target contrast C_R' when detected. Using paired values of C_R' and α from the scientific literature, the formula is plotted on graph paper. Intersection of the curve with a line of equality of the two axes of the graph enables finding α, hence detection range (from another derived formula) or finding apparent contrast when detection occurred.

To illustrate use of this graphic method, several examples were worked out in detail using the atmosphere only, atmosphere plus HUD, and atmosphere plus windscreen, HUD and spectacles. The advantage of plotting on semi-log paper was demonstrated. It was shown that the percent loss of detection range was much smaller than the contrast loss in percent attributable to the HUD. The discussion of the use of laboratory data to predict field performance leads to the conclusion that both actual target detection range and loss of range from loss of contrast by aircraft optics would be less than expected.

(H) CONCLUSIONS

(1) Computation of maximum target detection range is readily achieved by the graphic method derived in this paper. Values are required for the size and inherent contrast of the target, atmospheric clarity and contrast losses from optics such as aircraft windscreen, HUD and the pilot's visor and spectacles.

(2) The method derived is a graphic one so that answers will be influenced by small errors in plotting and reading of values on the graph. However, if reasonable care is used, repeated plotting can obtain ranges that differ by trivial amounts (less than 1%), even using linear vs. semi-log paper. A computer program could, of course, be generated to provide quicker estimates with even greater accuracy.

(3) Using semi-log paper is appreciably easier than using plain or linear graph paper, because the data lines that have to be drawn are much straighter and easier to draw.

(4) Use of contrast sensitivity data from the scientific literature to find detection ranges and loss of range attributable to aircraft optics will lead to biased results. Detection range in the field will be less than indicated, i.e., results from calculation are optimistic. However, loss of range attributable to aircraft optics will be pessimistic, i.e., actual range loss due to optics will be even less than that indicated by computation.

(5) In general, optics-caused loss of detection range is considerably less than contrast loss expressed as a percentage. A relatively large optics-caused contrast loss leads to a relatively small loss in detection range.

(6) Deficiencies in the applicability of conventional laboratory data in predicting performance in the field leads to the conclusion that field measures are necessary to supplement computational results.

(7) This paper utilizes contrast detection data based on observation of discs of variable size and contrast. The more recent methods employing contrast sensitivity for sine wave grating targets of variable contrast and spatial frequency viewed with and without aircraft windscreen and HUD can provide valuable data on how these optics influence vision, hence detection range.

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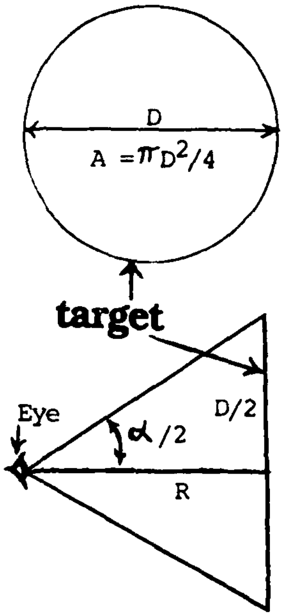
(A) THE ATMOSPHERE

$$C_R = C_o\, e^{-3.912R/V}$$

Solving this for R yields

$$\boxed{R = (V/3.912)\operatorname{Log}_e (C_o / C_R)}$$ Equation (1)

(B) THE TARGET OBSERVER GEOMETRY



A = Target Area $= \pi D^2/4$

$D = \sqrt{4A/\pi} = (\sqrt{4/\pi})(\sqrt{A}) = 1.1284\sqrt{A}$

For D in yards, A in square feet, divide by 3. Then

$D = (1.1284/3)(\sqrt{A})$

$D = .3761\sqrt{A}$ yards, A in square feet.

In the triangle:

$\operatorname{Tan}(\alpha/2) = (D/2)/R$ However, for small α,

$\operatorname{Tan}(\alpha/2) = (\alpha/2)$ radians $= (\alpha/2$ minutes$/ (57.3)(60))$*

$\operatorname{Tan}(\alpha/2) = (\alpha/2)/3438$ Thus,

$D/2R = (\alpha/2)/3438$, or

$D/R = \alpha/3438$ and

$R = 3438D/\alpha$, but $D = .3761\sqrt{A}$ (see above),

Thus:

$R = 3438(.3761\sqrt{A})/\alpha$, which simplifies to

$$\boxed{R = (1293\sqrt{A})/\alpha}$$ Equation (2)

(C) EQUATING ATMOSPHERIC R TO GEOMETRY R

$$(V/3.912)\operatorname{Log}_e (C_o / C_R) = (1293\sqrt{A})/\alpha$$

This reduces to:

$$\boxed{\operatorname{Log}_e (C_o / C_R) = (5058\sqrt{A})/\alpha V}$$ Equa (3

Fig.1.Derivation of the basic formula.

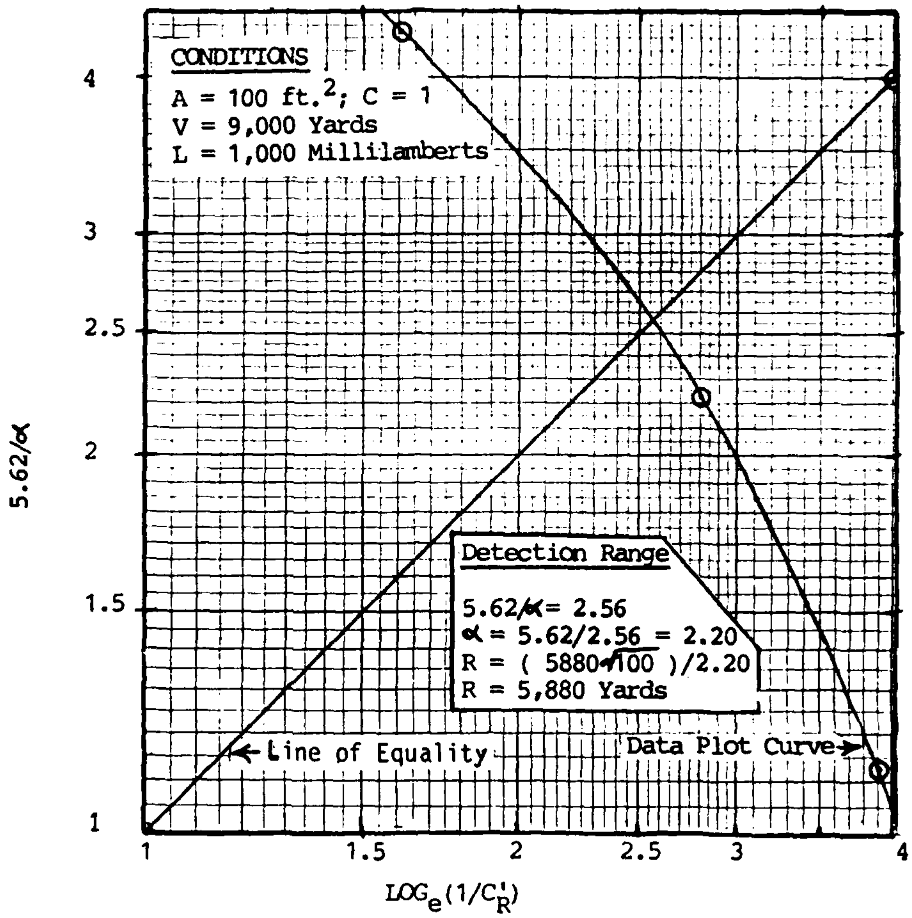


Fig. 2. Log-log graph paper plot of target detection range, contrast loss due only to the atmosphere. Note that the equal axis line, or line of equality, is straight, while the data plot is curved.

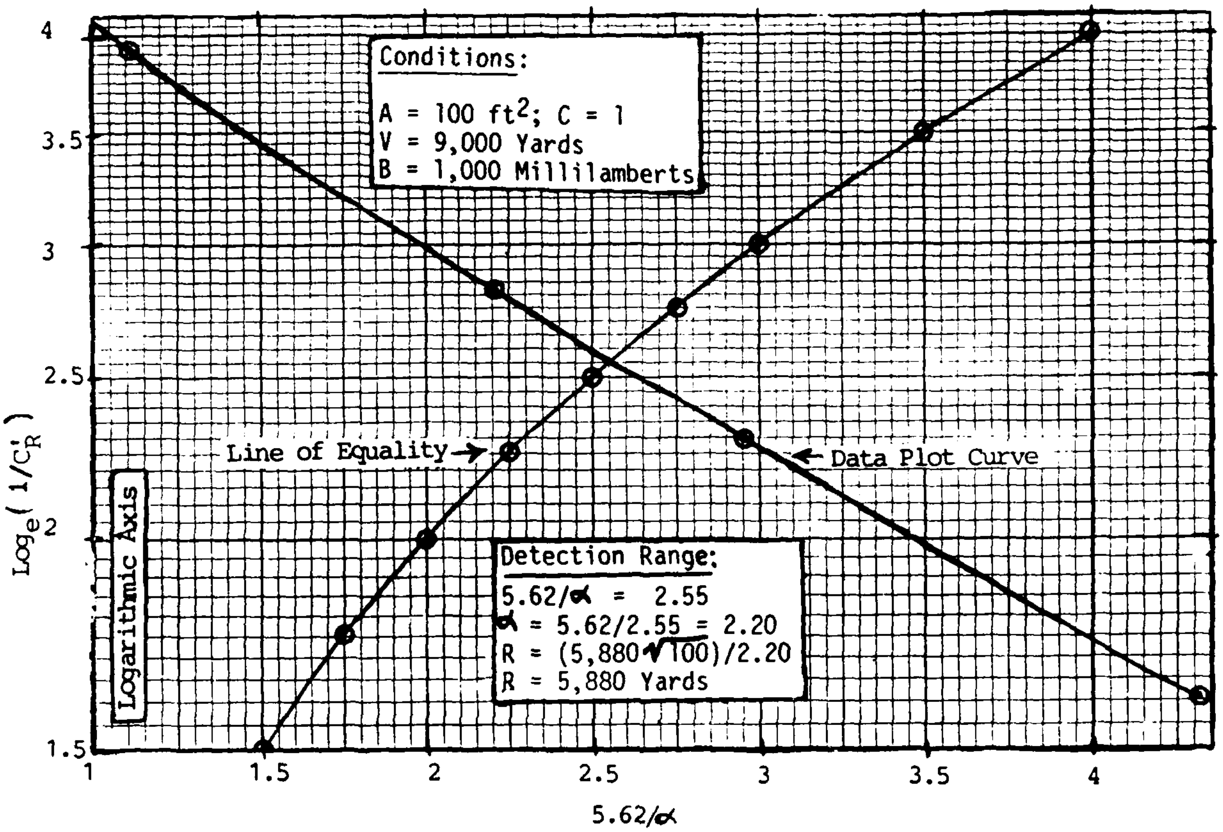


Fig. 3. Semi-log graph paper plot of example 1. Note that the equality-of-axes line is curved, but that the data points line is nearly straight.

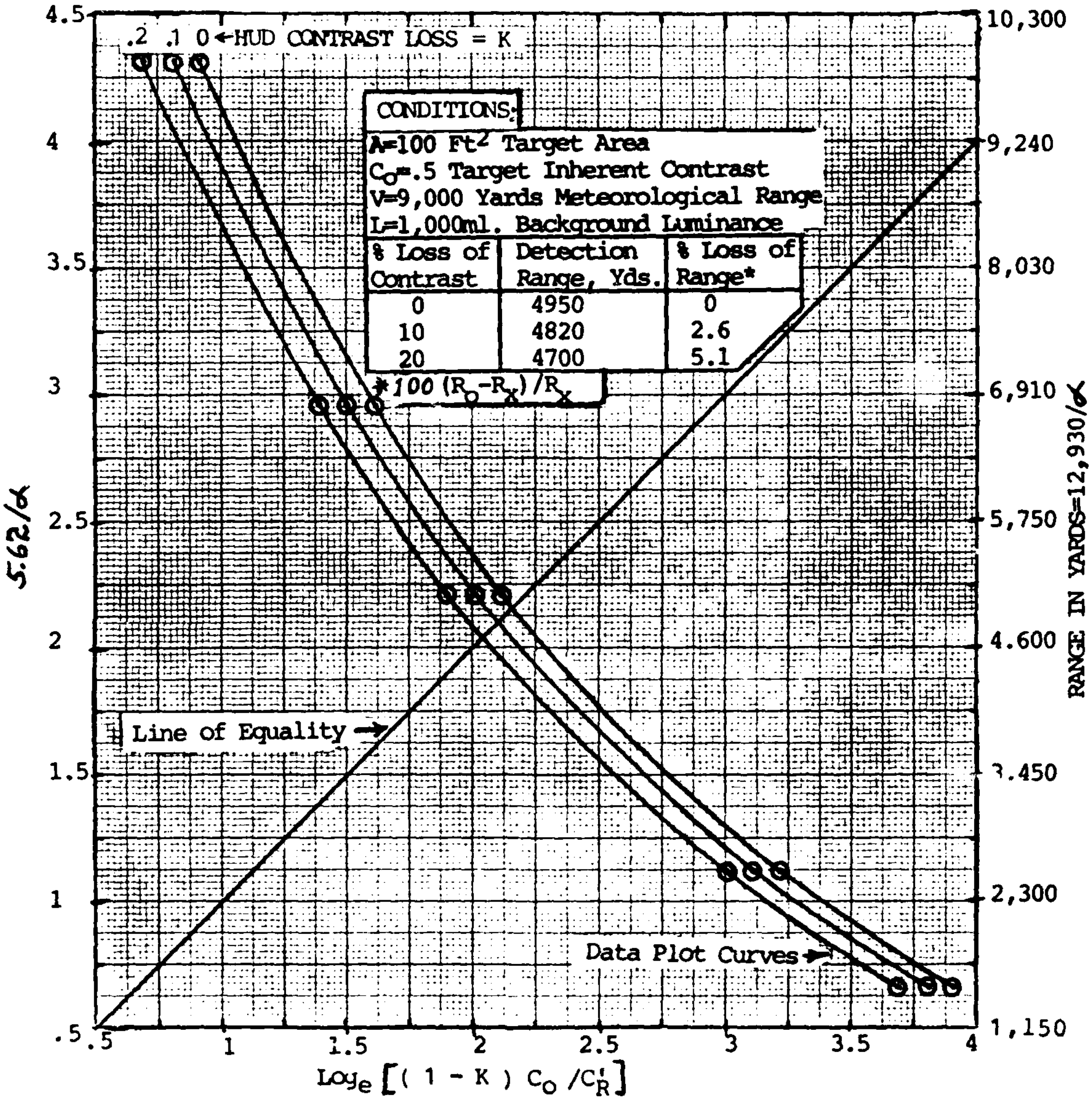


Fig. 4. Ordinary or linear-linear graph paper plot of example 2 for 0, 10 and 20% loss of target contrast due to a head-up display.

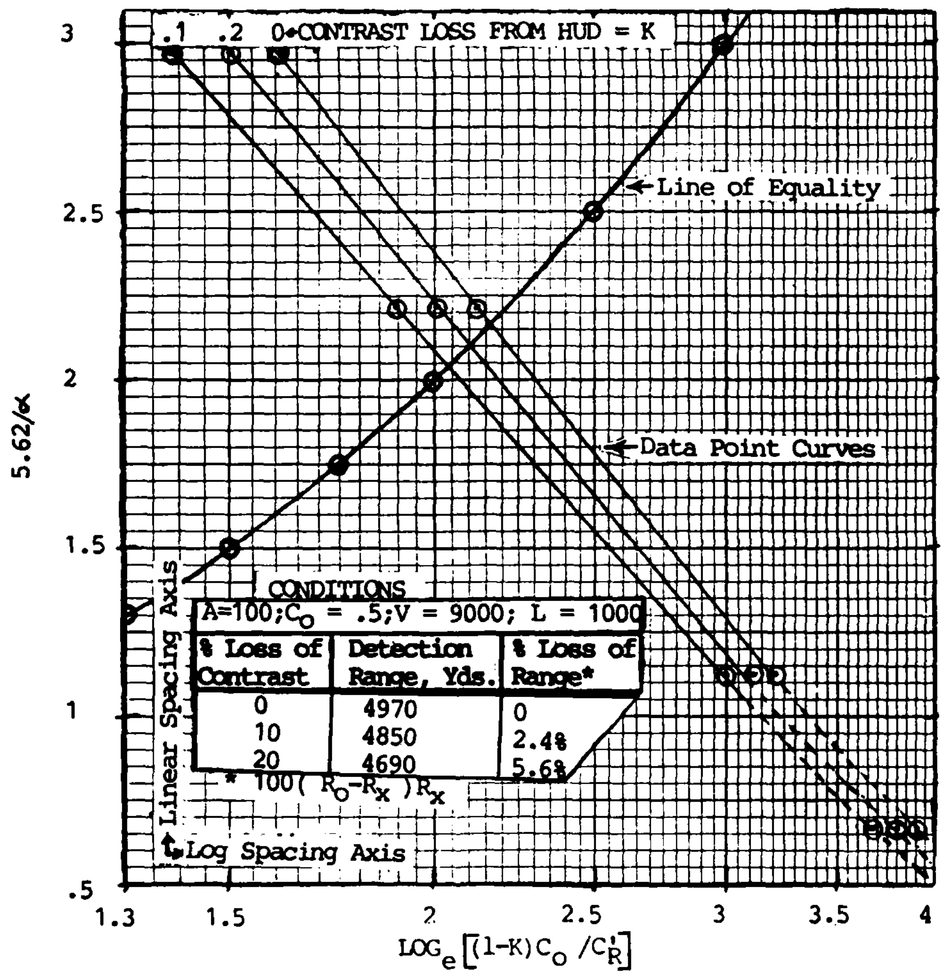


Fig. 5. Example 2 plotted on semi-log paper. Note that the equality-of-axes line is curved, but that the data point line is very nearly straight.

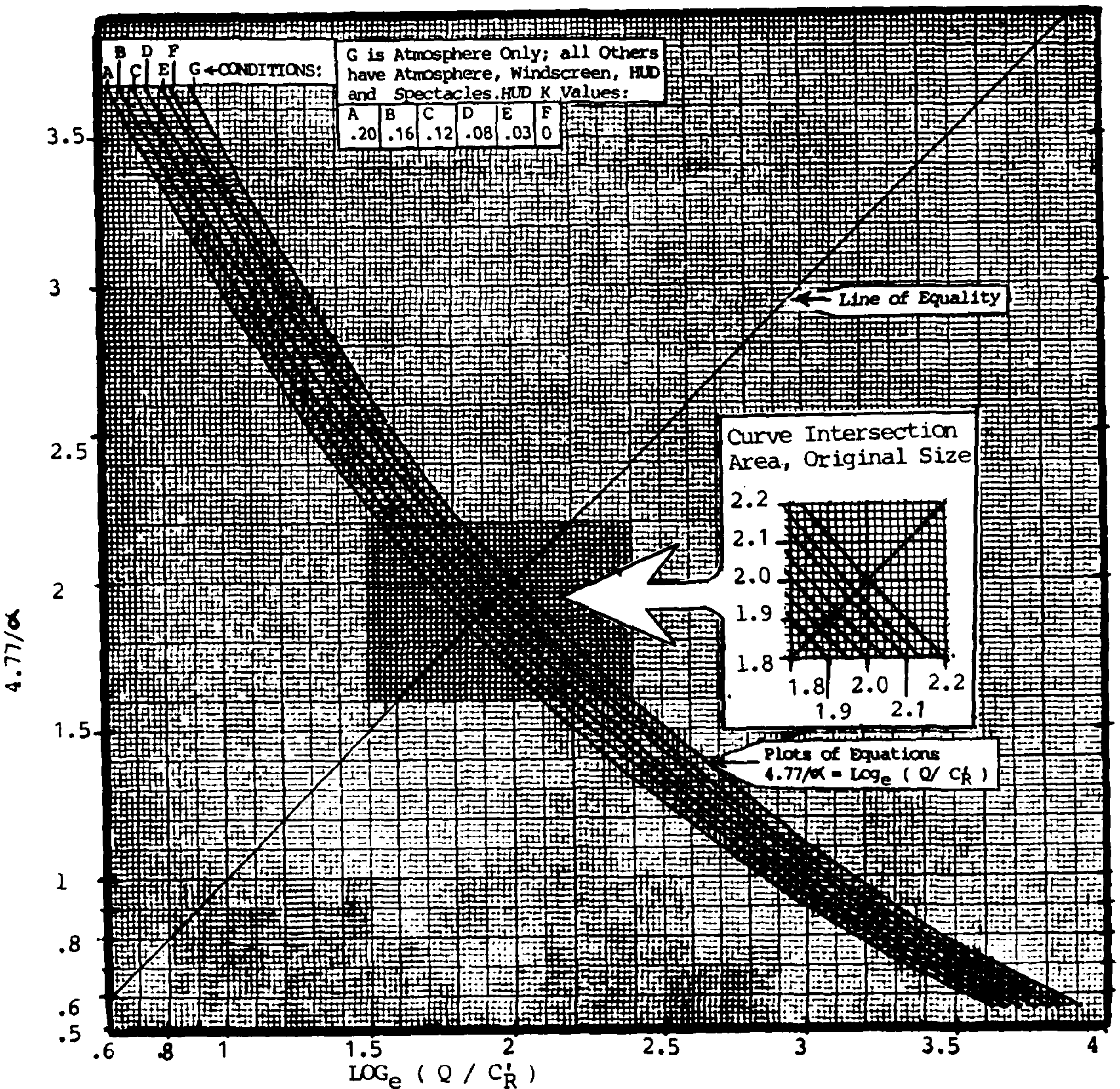


Fig. 6. Linear plot for the atmosphere only, and plots for looking through the atmosphere, the windscreen, spectacles and a head-up display, all in series. Plotted HUD-caused loss of target contrast covers the range of 0 through 20%.

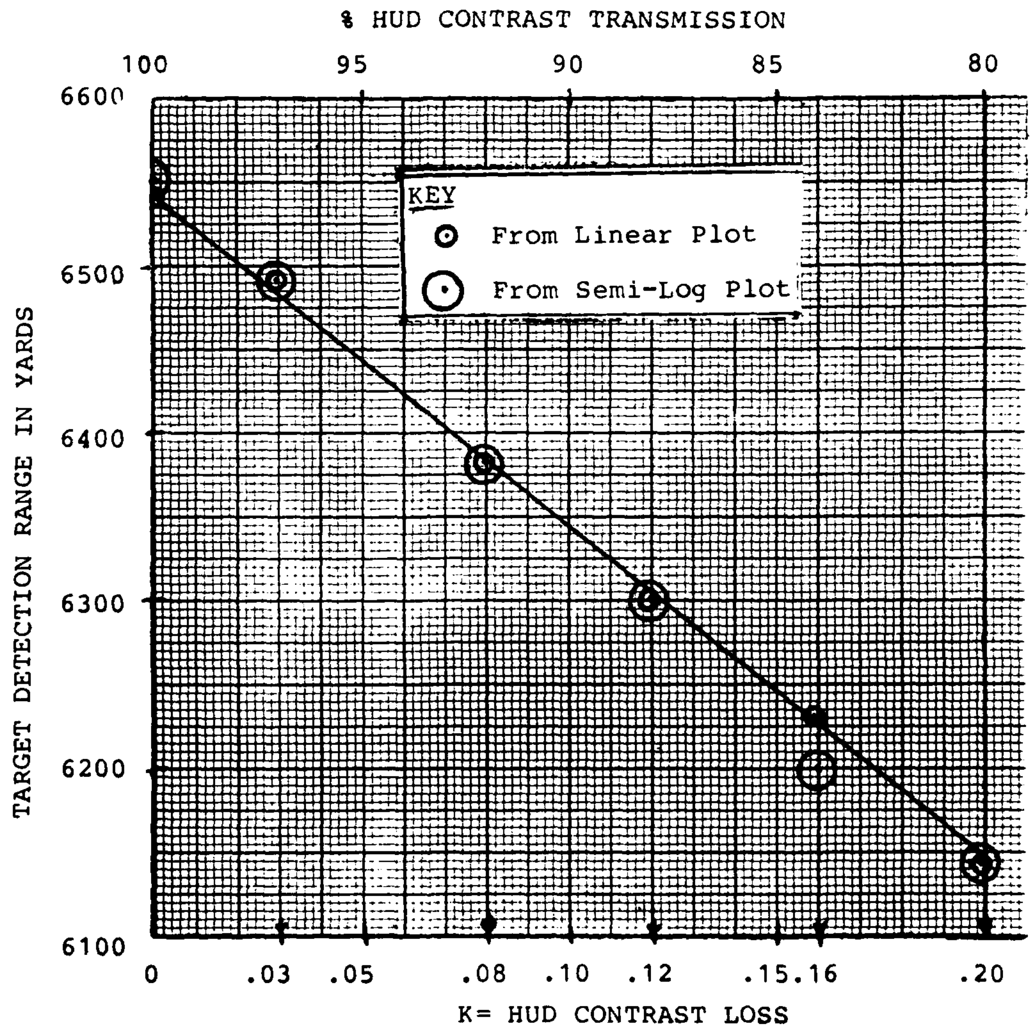


Fig.7. Target detection range for various values of HUD contrast loss.

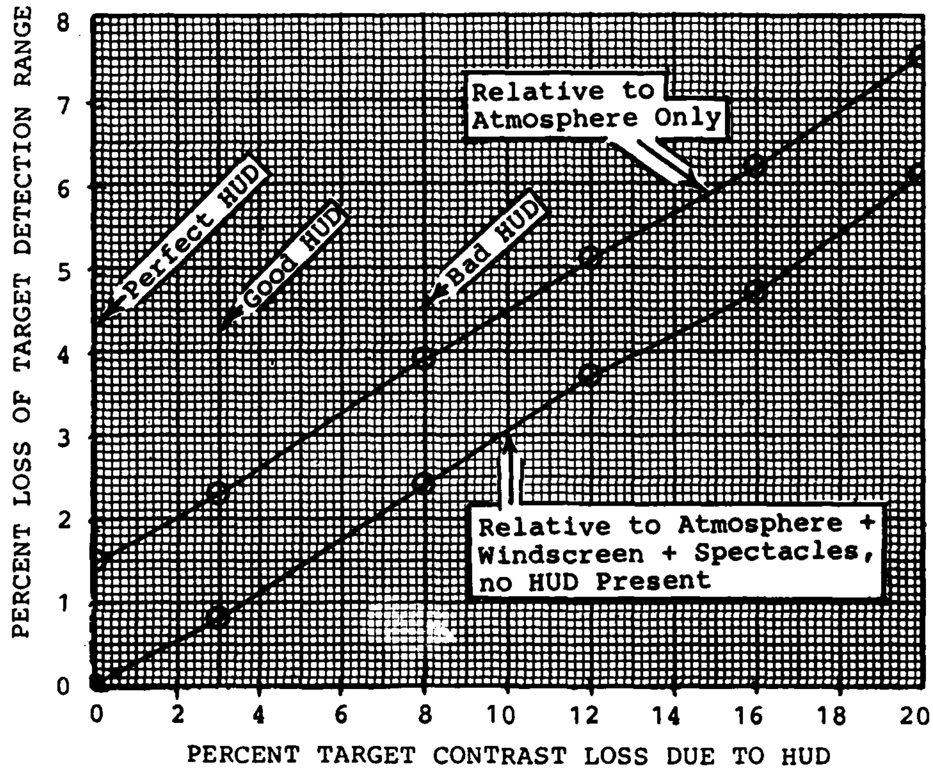


Fig.8 . Relative loss in target detection range with head-up displays having various contrast transmissions used with and without windscreen and spectacles.

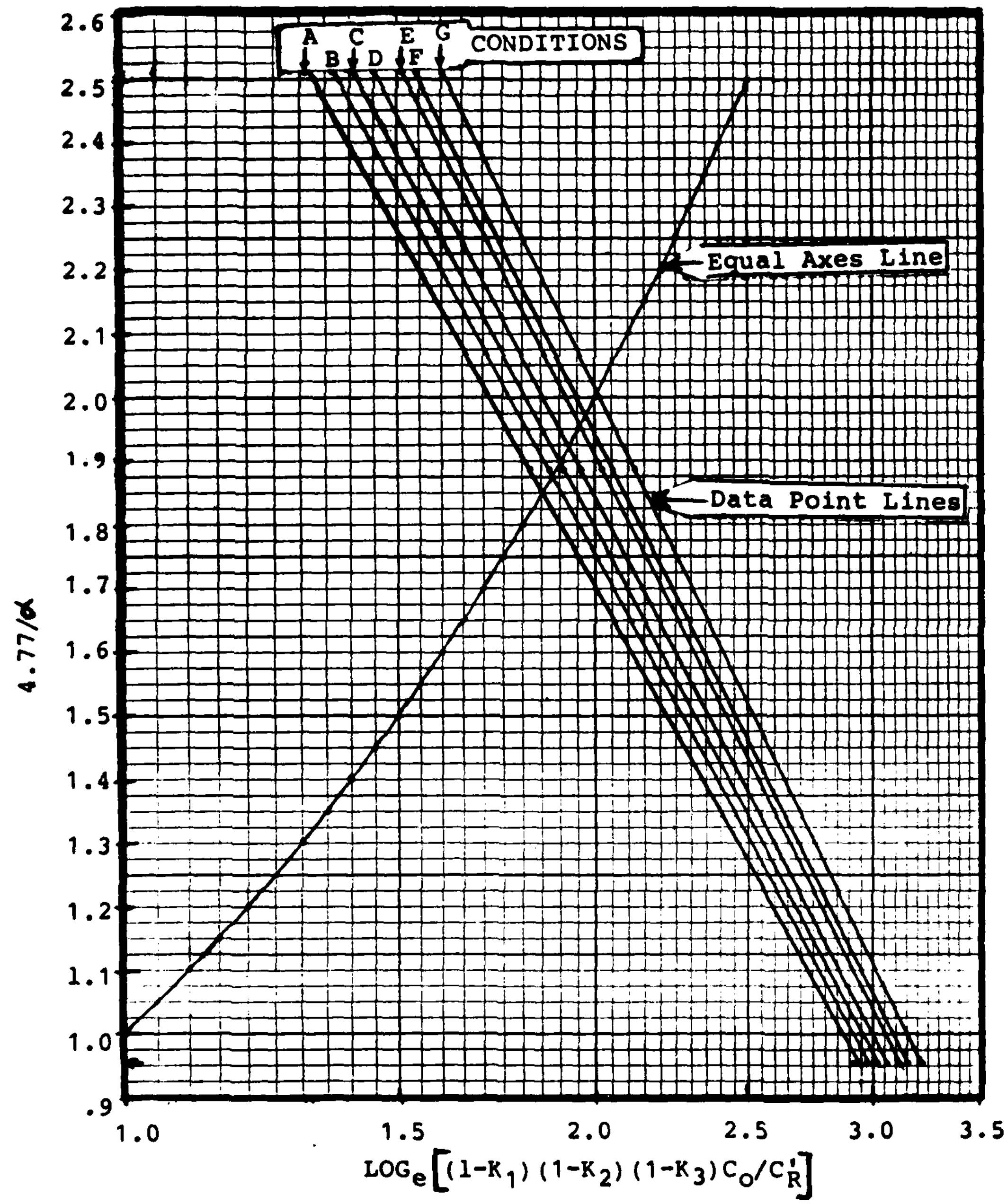


Fig. 9. Semi-log plot graph for obtaining target detection range for atmosphere, windscreen, head-up display and spectacles in series for various values of HUD contrast transmission.

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Direct Performance Assessment of HUD Display Systems Using Contrast Sensitivity

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Introduction: Present metrics for evaluating display systems rely heavily on physical measurements of various system elements. Depending on the display type, these may include limiting resolution, number of grey shades and transmission loss. Unfortunately, these kinds of metrics have not related directly to observer performance, such as detection range capability. A major problem with creating performance-related metrics has been the lack of analytical throughput, that is, the ability to characterize relevant target information in the same language used to specify system capability, visual processes and performance metrics such as detection range. Unified metrics of display quality are needed that directly relate target information to display capability and operator performance. Although the physics of displays are well understood, there has been a lack of understanding and inability to quantify visual target acquisition. However, increased understanding of visual science now, when coupled with linear systems analysis, promises to create unified performance-based metrics[1]. In particular, contrast sensitivity changes to sine-wave gratings imaged through a display system yield a contrast sensitivity function that can be related to detection range. The spatial frequency bandwidth of relevant target information can be related to changes in the contrast sensitivity function, which, in turn, can be related to changes in target contrast and detection range. This paper discusses an application of this approach for quantifying the detection range impact of several different head-up (HUD) displays.

Three candidate HUDs for the F-16 aircraft, two having similar refractive optics, AFTI and Production, and the third having reflective, holographic optics, LANTIRN, were evaluated by test pilots in field tests for mission performance. The pilots complained that the newer LANTIRN HUDs had several optical problems: color halos and patches, sun spots, glare, reflections, loss of targets and target contrast. Since the primary specification for the optical quality of the HUD, optical transmission, was met by the manufacturer, it was clear that a more relevant evaluation of the HUD was neccessary. For example, evaluating only the transmission quality of the HUD optics obviously excluded important factors that pilots complained about, such as glare, light scatter and reflections, that will vary greatly in different operational settings and reduce target visibility. These latter considerations call for a metric that can evaluate the HUD system with proper considerations of all possible detrimental effects on target visibility.

Contrast sensitivity functions were obtained from observers to sine-wave gratings viewed around and through the HUDs under laboratory and field conditions. Contrast losses resulting from the HUD optics (owing to transmittance, glare, and reflections) were translated into detection range losses using previously collected field trial data that related differences in aircraft detection range of Air Force pilots to differences in their contrast sensitivity. This approach is compared to previous approaches to specify visual performance through optical media. The results show that even though the optical system of the LANTIRN HUD is fundamentally different from the other two HUDs, in general, these three HUDs produce similar losses in detection range.

THE CONTRAST SENSITIVITY METRIC: The purpose of head-up displays (HUD) is to allow the pilot to simultaneously see targets and HUD symbology. Targets are visually acquired from their perceived contrast. Contrast, the luminance difference between the target and background, is needed for all aspects of target acquisition, including target detection and shape recognition. Any factor that reduces target contrast reduces target detection and recognition range. The factors that can affect perceived target contrast are target background, atmosphere, windscreen, HUD optics, visor, eyeglasses, and the visual system. Although the main concern here is the effect of the HUD optics on loss of target contrast, it is important to keep in mind that it is only one factor, admittedly an important one, that can affect target visibility. Some initial data will be presented that addresses the other factors that can affect target contrast.

An objective evaluation of the HUD system that relates to target acquisition requires measurements of changes in target contrast due to all possible HUD components that image the target. For example, the properties of optical transmissivity of the HUD system that can effect target contrast are lens transmission, light scatter, glare and reflections. Although each of these properties could be measured separately, unless these measures relate directly to contrast transmission then the overall effect of these factors cannot be used to determine detection range loss. Further, even if these measures are in terms of contrast, if each is measured separately, then their interactions will not be captured and cumulative assumptions of the individual measures will produce varying errors in performance assessment. Therefore, the primary target consideration for a metric required to determine the capability of the HUD to transmit target contrast is that it measure the effects of all the possible HUD contrast losses as well as their interactions. The visual system is the final receiver of target contrast and has a spatially distributed detection system in the form of receptive fields or channels whose spatial properties in terms of resolution and sensitivity vary across the retina. Unless a similar analytical model is used for evaluating HUDs, then conventional single spot or averaged contrast measures will not provide measures of contrast that can meaningfully relate to the human performance. Until a proven model of human vision is available, the human observer can be used as a contrast detector to determine the contrast transmission capability of the HUD system directly. Once the overall system performance is determined, then one can return to the physics of the individual system elements and determine their particular effect on the total system.

CONTRAST SENSITIVITY FUNCTIONS: Over the last five years, AFAMRL/HEA Aviation Vision Laboratory (AVL) research has developed a quick, sensitive and repeatable measure of contrast sensitivity, CS, based on a multi-channel vision model[2] that relates well to the target acquisition capability of individual observers[3-7]. Contrast sensitivity can also be used to help determine the contrast transmission capability of display systems such as HUDs. CS can be used to quantify the relative differences between contrast transmission with and without all or some components of the imaging system and then can be used to relate those differences to detection range.

The contrast sensitivity function, CSF, is a curve that describes an observer's threshold sensitivity to targets of different sizes. Contrast sensitivity, CS, is the reciprocal of the threshold contrast needed to just detect a target. The Michaelson definition of contrast is typically used for sine-wave gratings: C = the difference between the maximum and minimum luminances divided by their sum. Sine-wave grating targets are typically used because sinewaves are basic functions of complex objects (Figure 1a). Any spatial target can be decomposed into a combination of sine-waves using Fourier analysis. Since human vision shows a high degree of linearity around threshold, the visual response to the threshold gratings shows powerful predictive capability to more complex targets[2]. This general predictive power for individual target detection of complex targets has not been shown using other target sets or approaches.

Figure 1b shows a typical CSF having contrast sensitivity plotted on the ordinate and spatial frequency of the test grating in cycles per degree of visual angle, cpd, plotted on the abscissa. The CSF bandpass filter characteristic has peak sensitivity at about 3 cpd, falling slowly for lower spatial frequencies and more quickly at the higher spatial frequencies until reaching the cut-off limit of human vision, about 50 to 60 cpd.

Although it is conventional in the optical community to speak of contrast transmission of optical systems, optical systems can also be characterized in terms of their contrast sensitivity in the same manner as electronic systems are characterized in terms of signal sensitivity. Optical systems can act as frequency selective filters. Therefore, in order to underscore the ability of CS techniques to characterize the total optical system performance in a manner similar to visual performance, the CSF of the HUD is a measure of the capability of the HUD to transmit low contrast target information with the human observer as the contrast detector. The HUD CS was determined by measuring an observer's CS with and without viewing through the HUD. This technique uses the high visual sensitivity of the observer as a contrast detector whose visual sensitivity provides baseline control for all other test conditions. The general experimental set-ups for measuring CS in laboratory and under field test conditions are shown in Figures 2a,b.

The methodololgy and equipment used to measure the CSF of the observer with and without the HUD is described elsewhere[5,6]. Briefly, a microprocessor controlled portable computer automatically presents a series of gratings to the observer in ascending spatial frequency. A preview grating is presented for three seconds, to reduce observer uncertainty to the spatial frequency to be detected, then disappears to below threshold visibility. After a randomly determined time interval, the contrast of the grating is increased at a preselected slew rate. The observer presses a button when the grating first becomes visible. This procedure is continued for five measures after which time the next test grating is previewed and the test procedure is continued for the remaining test gratings. The CS difference between viewing the gratings around and through the HUD is the gain or loss of threshold contrast for the HUD. In general, there are three test conditions: baseline CS looking around the HUD, CS through the HUD, and for the AFTI HUDs and LANTIRN which had more optically dense upper portions of their display, the eyebrow, CS was measured through the eyebrow center.

DETERMINING DETECTION RANGE LOSSES FROM REDUCED CONTRAST SENSITIVITY: AVL field trial data correlated differences between the CS of pilots to differences in their detection range of an approaching aircraft[7]. Ten field trials were run over three months in which groups of usually ten pilots per trial were required to report detection of a T-39 aircraft flying towards them under visibility conditions ranging from 1.5 to 15 plus miles. Eight of ten trials yielded highly significant correlations to detection range and pilot CS and not to their visual acuity (a result incidently predicted from the multi-channel model[3,4]). These data, using the highest correlations from the 10 miles plus visibility conditions (to minimize possible criterion effects in the analysis) are shown in Figure 3. From an extensive study in the 1920s', Koschmieder determined relationships between target contrast and detection of high contrast ground targets under a variety of meteorological conditions[8]. The trends in that data are similar to those of the AVL field data. The fractional detection range reduction assosciated with the fractional contrast reduction from the pilot field study are plotted with the solid curve created from the Koschmieder data. The agreement between the two sets of data is excellent even though Koschmieder used stationary targets and the pilot field data came from detection of a moving aircraft. This relationship is used to determine detection range penalties from losses in CS of the HUDs.

HUD CONTRAST SENSITIVITY MEASUREMENTS UNDER LABORATORY CONDITIONS: The purpose of measuring CS under laboratory conditions was to establish as fair an evaluation of the HUDs as possible by producing a constant diffuse lighting environment corresponding to a reasonably homogeneous sky.

An AFWAL Terrain Board Facility was modified to create a booth approx. 24' long, 18' high and 8' wide. The right side was illuminated by a fluorescent light bank; the rear and front of the booth were illuminated using flood lamps. The luminance was 500-700 FL forward and to the left side and 1100-1400 FL to the right. The fluorescent lamps produce a mercury vapor spike at 540nm which would negatively bias the LANTIRN HUD. Therefore, the luminance was increased proportionately for the other HUDs. The resulting illumination produced a diffuse lighting environment that corresponded to a bright, cloudy day having the sun off to the right side of the HUD. The lights were also turned off to determine CS losses due only to transmission loss of the HUD optics.

The three CS test conditions were: baseline CS without the HUD, CS through the center of the lower HUD, and through the center of the eyebrow for the AFTI and LANTIRN HUDs. These three test conditions were run with high and low luminance conditions and with visor up and visor down.

The lights-off condition showed similar spatial frequency losses in contrast sensitivity for all HUDs that suggest similar transmission losses (Figure 4a). The lights-on condition showed similar losses for all spatial frequencies for all the HUDs that suggest similar light scatter, glare, and reflection losses (Figure 4b). Large losses in CS were found for both the AFTI and LANTIRN eyebrows (Figure 4c)*. No significant differences in CS were found between HUDs for average viewing conditions (Figure 4d). The visor produced the greatest high spatial frequency losses (Figure 5a,b).

HUD CONTRAST SENSITIVITY MEASUREMENTS AT EDWARDS AFB: The purpose of the HUD CS measurements at Edwards AFB was to validate the HUD CS measurements in the laboratory under real-world luminance conditions. In particular, it was important to obtain HUD measurements under sun conditions that could not be readily simulated in the laboratory.

Three F-16 aircraft, each having one of the three HUDS (AFTI, Production and LANTIRN) were parked parallel to each other on an unused revetment in a direction perpendicular to the sun's path at zenith. That direction was determined to insure that the sun would not enter the acceptance cone of the HUDs and cause "sunspots" for some sun angle conditions for one HUD and not the others. The sun's path transcribed an arc that started at sunup about 30 degrees azimuth from the nose of the aircraft, peaked at about 40 degrees perpendicular to the aircraft and finished at sundown about 150 degrees azmuth from the nose of the aircraft. The luminance of the horizon haze in front of the aircraft was 2000-2300 FL and 500-700 FL overhead. The main CS measurements were completed between sunup and sun-zenith. Opaque black cloth was taped inside the upraised canopies to prevent canopy reflections on the HUDs. Three CSF testers were used to simultaneously measure CS, one for each aircraft, testing the same pilots used for the laboratory studies. The pilots switched aircraft after each CS test session to counterbalance the measurements. The three test conditions were as before: baseline CS without the HUD, CS through the center of the lower HUD, and through the center of the eyebrow for the AFTI and LANTIRN HUDs.

The LANTIRN and Production HUDs had generally larger CS losses than did the AFTI HUD for CS measured in the center of the HUDs (Figure 6a) and for average viewing conditions (Figure 6b). The AFTI HUD showed largest CS losses in the eyebrow for higher spatial frequencies primarily due to transmission and glare. The LANTIRN HUD showed large

* Data point asterisks indicate statistical significance for $p \leq 0.05$.

losses in the eyebrow at lower spatial frequencies primarily due to reflections. Unlike the laboratory data, there are small, though significant CS differences between HUD viewing conditions (Figure 6c). These small differences are due to the averaging of opposite interactions of various HUD losses occurring during the field tests.

General Discussion: The contrast sensitivity measurements obtained from both the laboratory and field test conditions show systematic and consistent losses in contrast that relate well to the physics of the different HUDs and the different test conditions. Although these data are valid for similar viewing and luminance conditions, further tests are needed to broaden the scope of these results, especially for the pilots' visor which showed higher losses at the higher spatial frequencies than any HUD. On average, the visor alone produced 40% CS loss whereas the HUDs produced half that loss, about 20%. Tinted canopies may show high losses in CS too. The losses in CS due to light scatter were similar in nature to those found in previous AVL studies on CS losses due to windscreen haze. Further, the CS losses were similar to those obtained from earlier studies accomplished by the AVL with a pre-production HUD.

In general, even though the three HUDs have different optical configurations that produce different sensitivity signatures, they show similar average detection range penalties of 6-8%. Losses in detection range will cause increased detection time and increased workload for the pilot. These data can be used in conjunction with mission requirements to create performance-related standards for HUDs. The similar average detection range penalties for the three HUDs evaluated here demonstrate the power of the CSF approach to provide total system analysis for quite different optical display systems and relate system performance to detection range loss.

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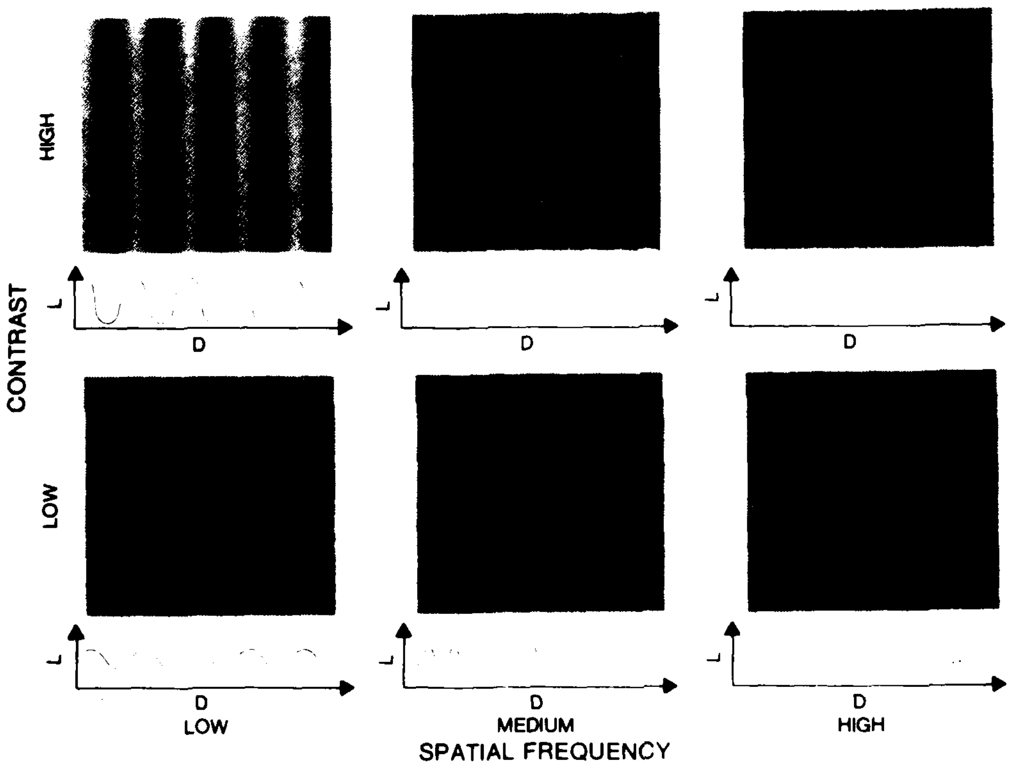
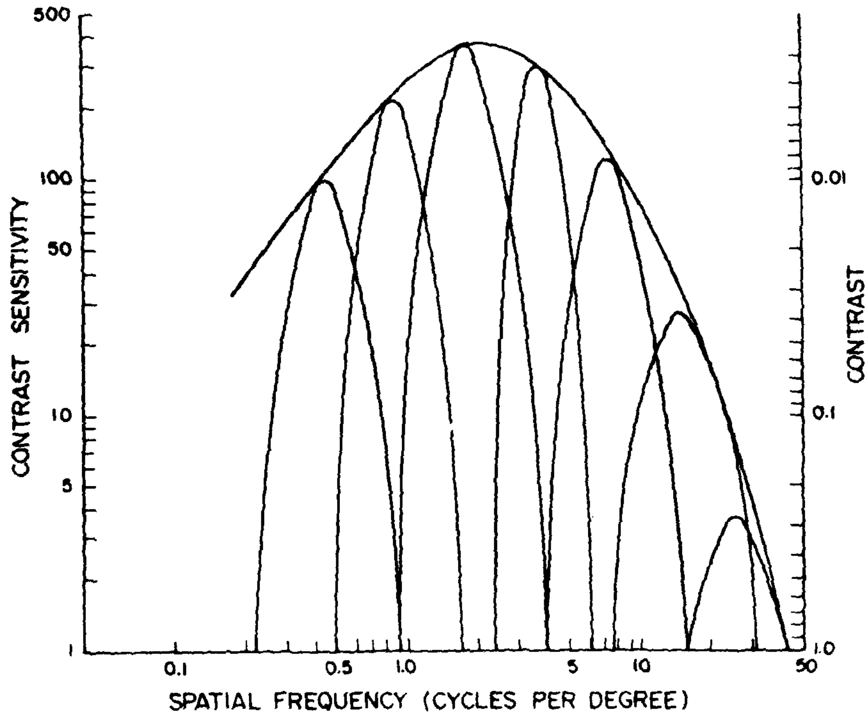


Examples of sine-wave gratings with low, medium and high spatial frequencies at low and high contrast. The luminance distribution for each grating is shown below each grating patch. Note that these gratings will have different visibilities depending upon viewing distance due to the visual filtering characteristics of the observer (Ginsburg, 1978).

Figure 1a



A typical threshold contrast sensitivity function is shown by the wide-band inverted U-shaped curve. Note that the visual system is most sensitive to threshold sine-wave gratings at about 2 cpd and is limited to passing spatial frequencies greater than about 60 cpd. The narrow-band curves represent channel filters based on biological data (Ginsburg, 1978).

Figure 1b

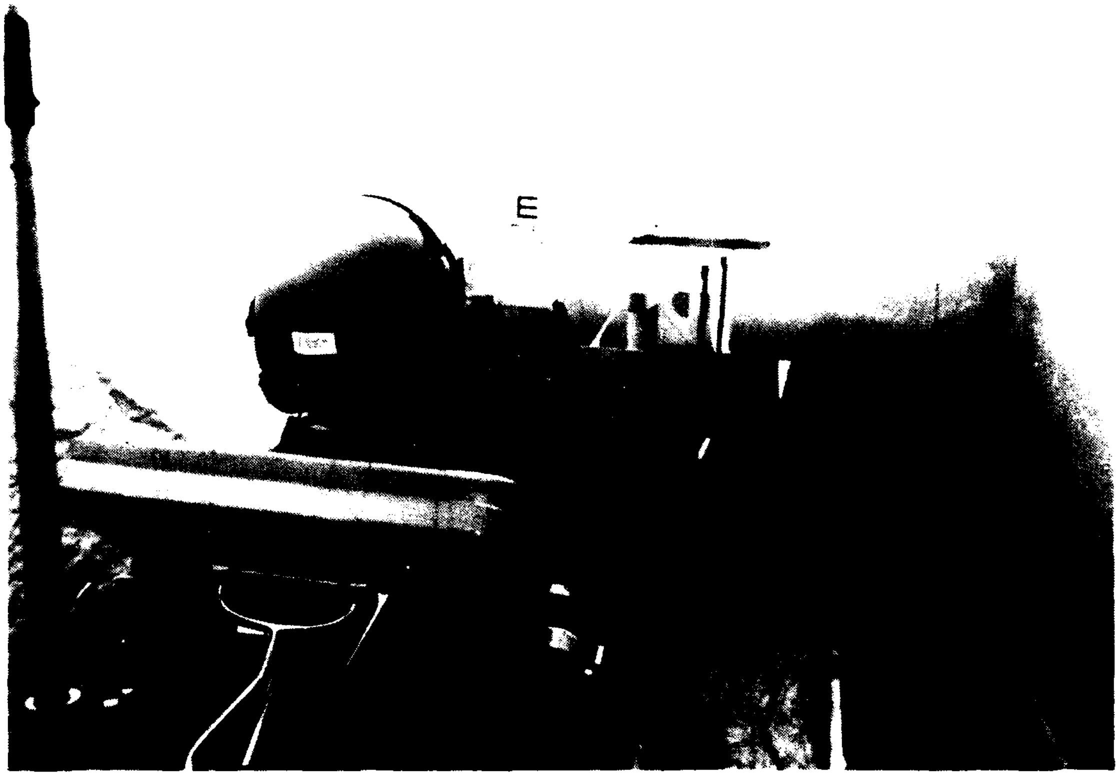


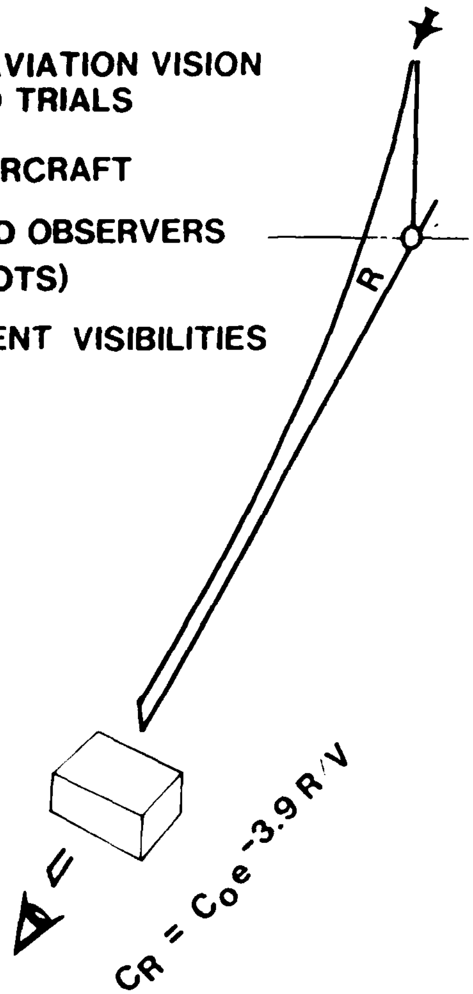
Figure 2a

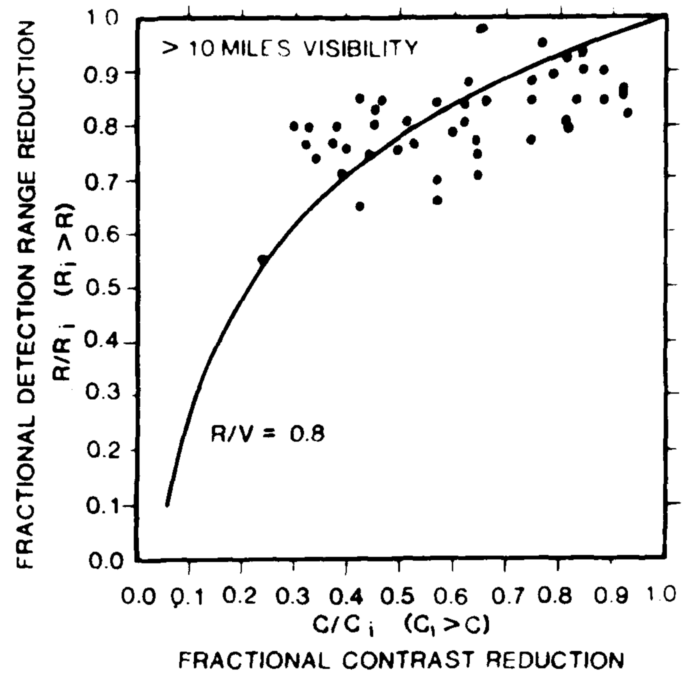
Figure 2b

CORRELATION BETWEEN TARGET VIEWER CONTRAST SENSITIVITY/VISIBILITY/DETECTION RANGE

AFAMRL AVIATION VISION LAB FIELD TRIALS

- T-39 AIRCRAFT
- GROUND OBSERVERS (AF PILOTS)
- DIFFERENT VISIBILITIES





- TESTS CORRELATED DETECTION RANGE WITH
  - VISIBILITY
  - OBSERVER CONTRAST SENSITIVITY DIFFERENCES
- METHODOLOGY FOR HUD ASSESSMENT

Figure 3

CONTRAST SENSITIVITY LABORATORY DATA

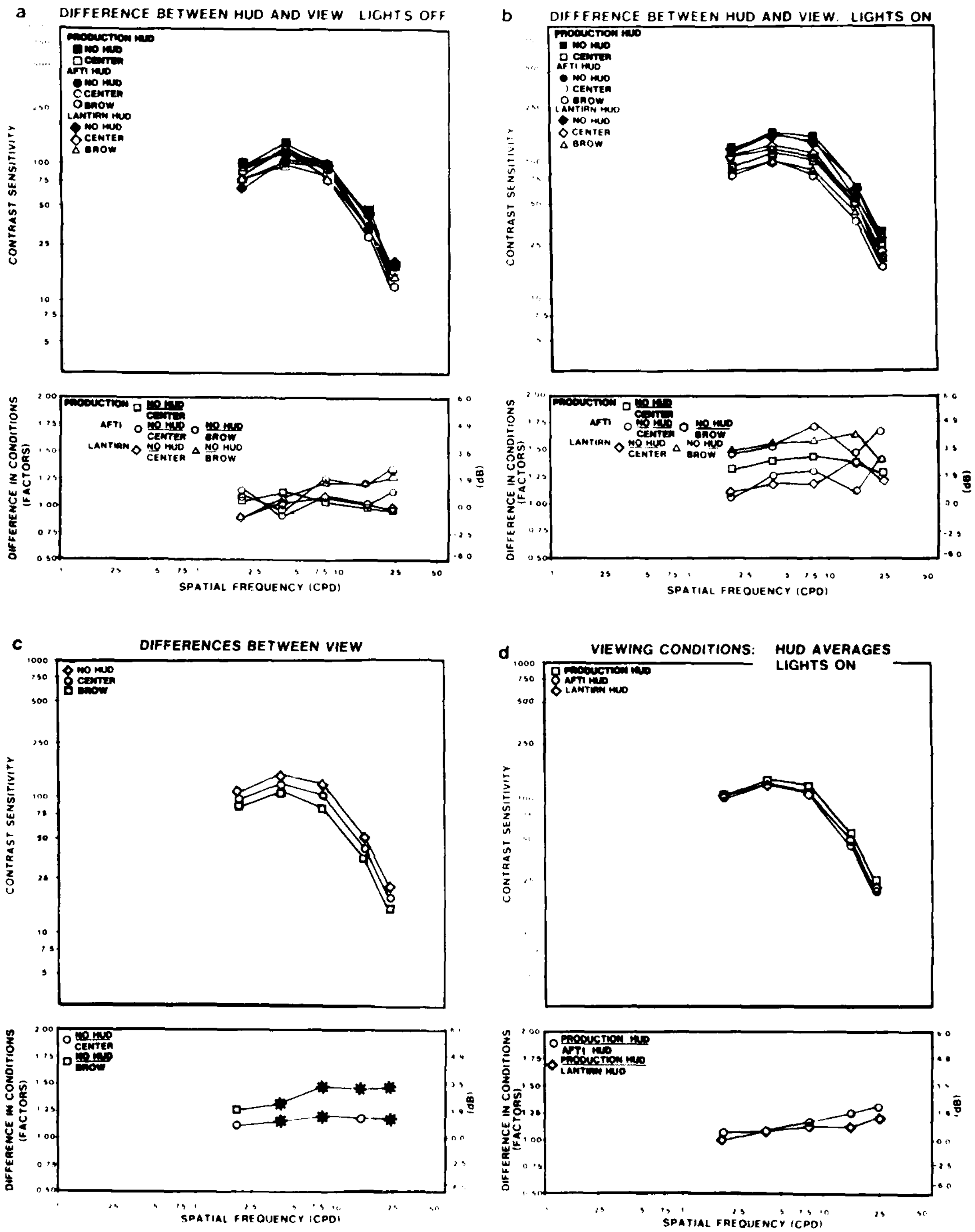


Figure 4

CONTRAST SENSITIVITY LABORATORY DATA

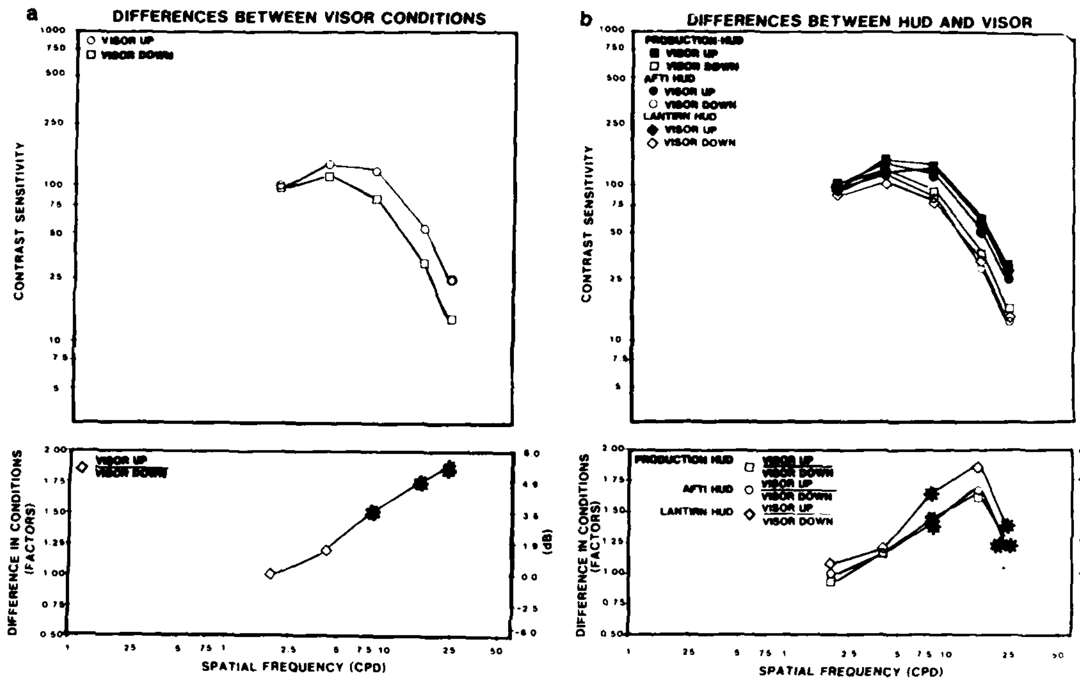


Figure 5

CONTRAST SENSITIVITY FIELD DATA

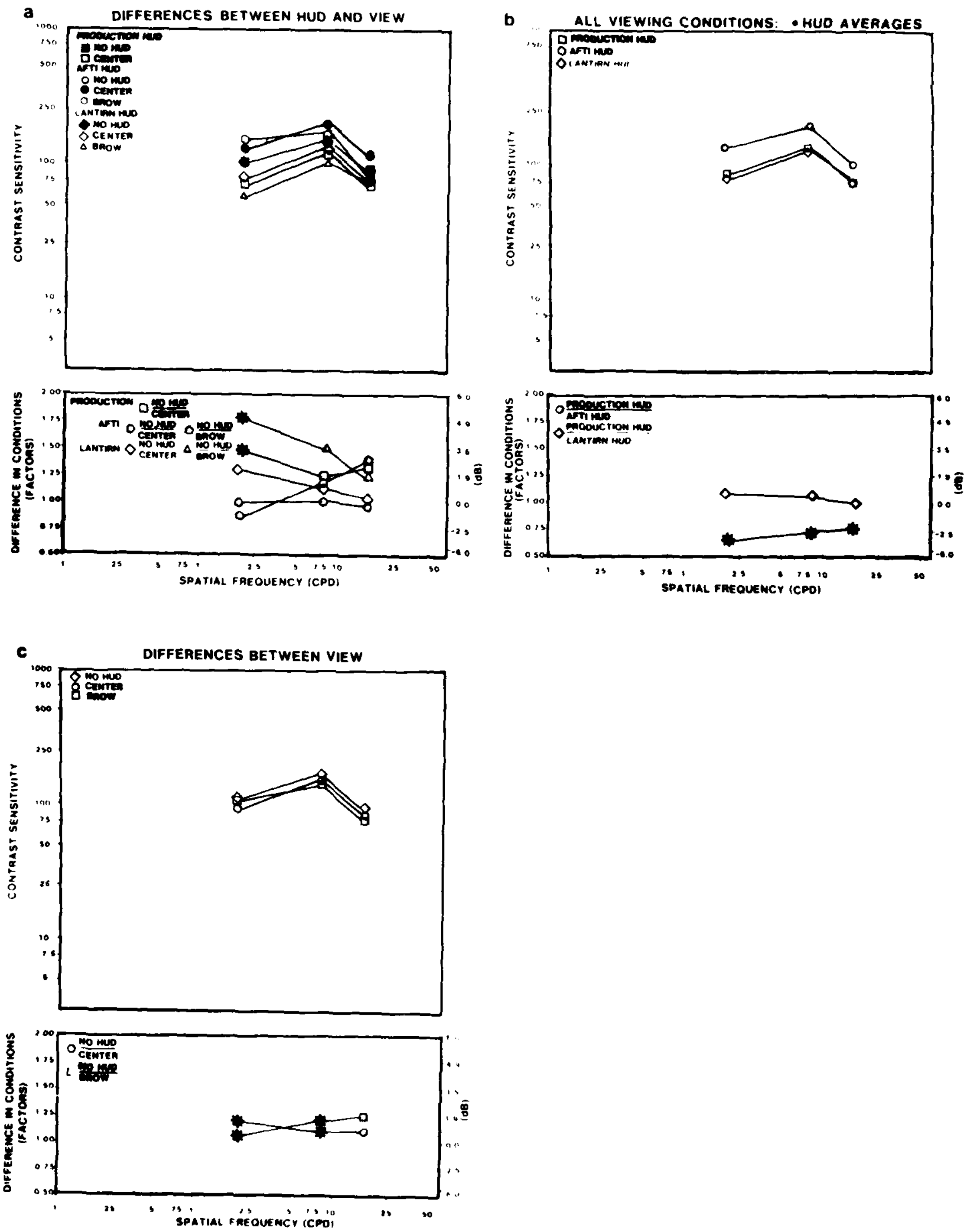


Figure 6

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PHYSICAL INTEGRATION OF THE HUD

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The physical integration of the HUD into the aircraft crew station used to be a relatively simple matter once the basic design parameters for the crew station were established, particularly the over-the-nose vision angles and the location of the design eye. The HUD was then mounted in the upper portion of the instrument panel and integrated into the surface of the glare shield, along the over-the-nose vision angle, with the optics oriented so that the center line of the collimating bundle passes through the design eye. There were minor problems with this method, the most notable being a tendency for pilots to sit higher than the design eye. The integration of the new LANTIRN HUD into the F-16, however, brought a whole new set of problems, but first let us discuss current design procedures.

There are several physical design constraints on the location of the HUD using current design practice, including:

- Design Eye Location
- Over-the-Nose Vision Angles
- Ejection Envelope
- HUD Display Unit Size
- Instrument Panel Location
- Other Physical Obstructions
- Windshield and Canopy Profile

The constraining factors are graphically illustrated in Figure 1. To illustrate how the HUD integration process works, we must first review the process of geometric arrangement of the crew station. As stated above, the fuselage contours required to provide the specified external vision are established, then the design eye is located along a line tangent to the forward fuselage contour, providing the specified over-the-nose vision. If conventional upright seating is to be used with the standard 13° backrest angle, then the neutral seat reference point (NSRP) is established along the backrest line 31.5 inches vertically below the design eye. The backrest line is located 13 inches from the design eye on a line perpendicular to the backrest line. After locating the NSRP, all the other fixtures (control stick, rudder pedals, instrument panel, etc.) are located with respect to it.

The ejection envelope is defined as the space that must be kept clear of all objects on ejection-seat-equipped aircraft to eliminate potential sources of injury to the crew member during ejection. Normal requirements call for the ejection envelope to be the volume swept by a plane perpendicular to the ejection seat rail angle, 26 to 30 inches wide and 30 inches forward of the front of the seat back with a six inch radius at the forward corners, sweeping up the rail angle. The ejection envelope is illustrated in Figure 2. All of the cockpit fixtures must be located outside the ejection envelope, with the exception of the control stick. If a control wheel is used, its width requires that it must be moved out of the ejection envelope during ejection initiation.

The other major constraining factor on HUD integration is the windshield and canopy. The canopy shape and location is usually governed by the combination of vision requirements, aerodynamic considerations, and crew member head clearance, normally specified as a 10 inch spherical radius around the design eye.

When values for all the above factors have been selected, the HUD is designed to fit into the space that is left and, with a conventional refractive optic HUD, oriented to pass the centerline of the collimating bundle through the design eye.

The process defined above is not an extremely complex one, particularly considering that all of the steps but the last one must be performed whether or not the aircraft has a HUD. That is not to imply that current HUD installations are without problems. The constraints on HUD location force the HUD to be so far from the pilot's eye that, even with very large conventional optics, the field of view (FOV) is limited. The 10 inch spherical radius head clearance requirement provides adequate head clearance within the canopy, and it provides the crew member latitude to adjust himself above the design eye which, in turn, forces him to slouch to use the HUD. Most of our current HUD-equipped aircraft have had expensive modifications to relocate the collimating bundle, increase the FOV, or both.

When the F-16 was developed, the installation of the initial refractive optics HUD was designed in much the same manner as that described above. The General Dynamics Corporation performed mock-up studies with a limited number of subjects to determine the design eye location, since the reclined seat with a 34° back angle was an unconventional design and something of an unknown. The reclined seat did not fit the "rules" established for cockpit integration with the conventional upright seat (near 13° back angle). Typical of other HUD installations, the "gripes" began to roll in from the field that pilots had to "hunch down" to see the imagery and that the FOV was too small. The first action taken was to perform a study using pilot subjects in the aircraft, with a larger sample size than the original mock-up studies to determine how the pilots were actually located in the cockpit. This study, performed at the Air Force Flight Test Center (AFFTC) at Edwards AFB, resulted in the centerline of the collimating bundle being raised 1 1/2 inches at the design eye. The test subjects were limited, however, to AFFTC test pilots.

The Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) program was initiated to provide an improved night navigation and weapon delivery capability for F-16 and A-10 aircraft. In addition to the navigation and targeting sensor pods, new HUDs were to be developed with an extremely wide angle FOV and the capability to display both raster imagery and stroke written symbology. The LANTIRN HUD selected uses a combination of reflective and diffractive optics to meet the wide angle FOV requirements. The reflective optics are pupil-forming, which means there is a limited envelope in which the imagery is visible. This envelope not only limits movement of the pilots' eyes up and down and side to side, as refractive optics do, but also limits fore and aft movement. The F-16 LANTIRN HUD was designed using the eye motion box that had been defined for the original F-16 HUD from the AFFTC study. When the first test model was installed in an F-16 at AFFTC, once again the complaints rolled in. Pilots were having problems with sudden visual loss of HUD imagery, internal flaring, reflections, sunspots and a multitude of other difficulties. The HUD contractor claimed that many of the problems being reported were caused by the pilots' eyes being outside the eye motion envelope. This claim was reinforced by the contractor's representative at AFFTC who felt that the pilots were sitting forward of the limits of the eye motion envelope. Once again we found that, even after two study efforts, we really did not know or understand how the pilots were sitting in the F-16. The first test installation of the LANTIRN HUD in the A-10 did not encounter the same major problems experienced in the F-16, due to our better understanding of body dynamics and positioning with the conventional upright seating. Since we did not fully understand the impact of reclined seating in the F-16, the next step was a study effort to define the limits of head/eye motion for the full population of the F-16 pilots. This time, the head/eye position data were recorded on videotape using a TV camera and target board. The data were taken in actual aircraft using both AFFTC personnel and operational personnel from Nellis AFB. The data recorded included head/eye position in normal, reclined, and alert positions. Reduction of the data indicated that the pilots' actual eye positions were lower and much further forward than had been originally assumed. A new eye motion envelope defined as a result of this study incorporated over 90% of the measured eye positions. The LANTIRN HUD for the F-16 is now being redesigned to provide a proper motion eye box location and, as a side benefit, the HUD combining glass assembly was reduced in size without reducing the FOV.

Since the currently used design procedures continue to allow problems to occur in the process of integrating the HUD, perhaps a new design procedure is required. Many of the design constraints will remain the same regardless of the procedures used; however, with the combination of new and unusual crew station geometries and new types of optics with varying constraints on eye and head motion, ways must be found to cope with these problems. The following will present a philosophy for a different methodology.

To provide the optimum physical integration of the HUD into the airframe, it is imperative that the HUD integration problems be resolved first and then the crew station be designed around the HUD limitations, rather than vice versa as is normally done.

First, the over-the-nose vision requirements must be established. The parameters that must be considered in making this determination include required vision angles and aircraft angle of attack during landing, required reticle depression angles for the various air-to-ground weapons, launch envelope of air-to-air weapons, lead angles for the aircraft gun within the maneuvering envelope in which it can be fired, plus any other visual tasks that may be postulated to have an effect on over-the-nose vision requirements.

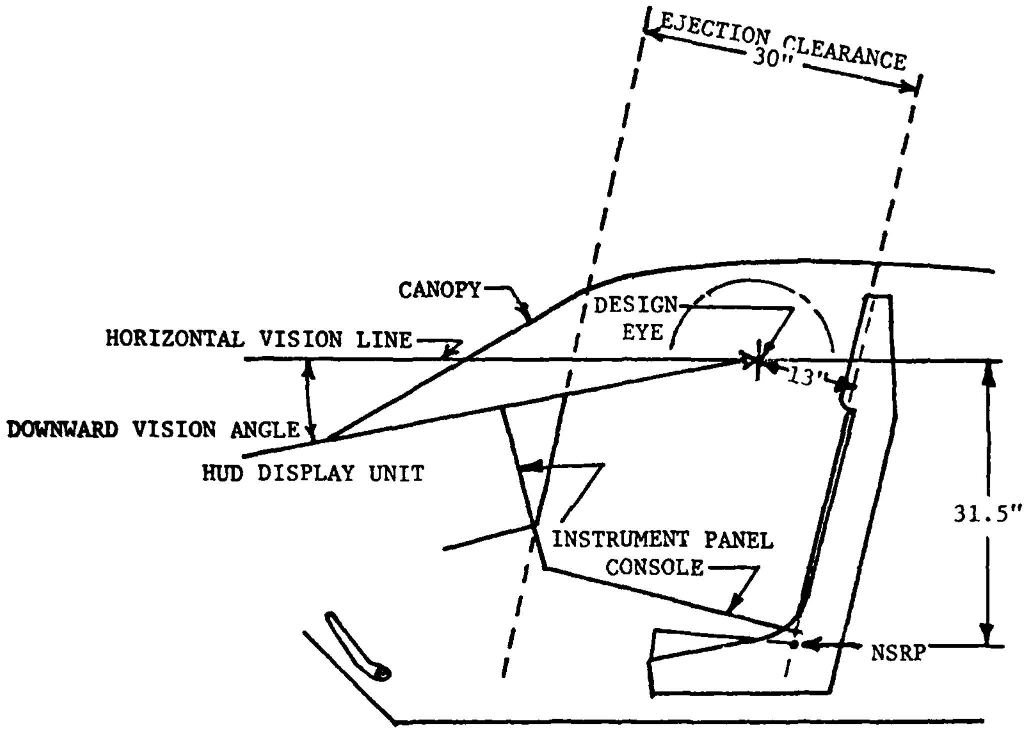
The type of HUD optics to be used should be established early in the design process. This is particularly important since, by this new philosophy, the constraints established by the FOV requirements and eye motion envelope limitations will be a major factor in the location of the man within the system. The use of reflective or reflective/diffractive optics appears to provide some flexibility in location of the eye motion envelope in that, while it is somewhat more constraining, having limitations in all three dimensions, the location and size of the envelope can be changed at will during the design process. Refractive optics, on the other hand, do not have this type of flexibility since, although the eye motion envelope is only constrained in two dimensions, those two dimensions are irrevocably established by the size of the collimating lens. Once that is established, the only design flexibility is in the direction that the collimating bundle is aimed. Now that an over-the-nose vision angle and eye motion envelope have been selected, the forward fuselage contours and crew station location can be defined and the eye motion envelope located with respect to them.

At this time an eye reference point should be defined, and is probably best located at the centroid of the eye motion envelope. What this eye reference point specifically relates to will be determined by the type of crew station geometry to be used. Although this article assumes that a fixed seat geometry is to be used, the techniques outlined should also apply to a variable geometry. Physically accomplishing them, however, may be much more complex. The eye reference point must, of course, be at the most likely position of the eye when using the HUD. In a geometry with conventional upright seating, near 13° back angle, the eye reference point will very nearly approximate the classical design eye. In reclined geometry, such as in the F-16, the eye reference point will more closely approximate what has been defined as the alert eye position. In any case, the decision regarding seat angle must be made. Upright seating is recommended for a number of reasons; 1) the physical HUD integration is easier. 2) it has the least impact on available instrument panel space, and; 3) reclining angles of nearly 65 degrees are required before any significant improvement in "G" tolerance is realized. There are circumstances, such as the need for reduced fuselage cross section for aerodynamics or radar cross section reduction, that may justify a geometry reclined to a less extreme angle. Once the geometry is selected, a preliminary layout of the cockpit should be made, fitting the HUD in place with respect to the previously defined eye reference point.

The next step is an extensive mock-up evaluation of the initial layout. The subjects for this evaluation should include operational tactical pilots. There should be as many as is practical to include and, in particular, subjects that approximate 5th and 95th percentile pilots should be included. The mock-up should incorporate a HUD or a device that requires the pilot to position himself as he would to use a HUD. Data must be carefully taken regarding eye location for using the HUD comfortably. When the data is reduced and the mean eye position established, the geometry should be revised to bring the mean eye position in coincidence with the eye reference point and to accommodate as many of the data points as possible within the eye motion envelope. Changes to the adjustment range of the seat may be required to accomplish this. The mock-up should then be modified to reflect the changes and be reevaluated on the same guidelines This is an iterative process that should be applied until further improvements are insignificant. In some cases, it may be more practical to modify the eye motion envelope than the geometry. The development of the HUD hardware and the crew station geometry can then proceed in parallel as opposed to serially, as is usually the case. All of the old crew station design constraints that have plagued us in the past are still there and must still be considered, but the primary difference with the procedure outlined here is that HUD integration is a primary, early consideration and not an afterthought.

Finally, the windshield design is an important factor in both the physical and optical integration of the HUD with the airframe. The problem of diplopia has been discussed at length in a previous section. The HUD/windshield diplopia problem is primarily caused by curvature of the windshield in a horizontal plane. The bending of light rays passing through a curved windshield disrupts the parallelism of the light rays. Obviously, the optimum solution to the problem, from the standpoint of HUD usage, is a flat panel windshield. Thus only the vertical refractive effects must be compensated for, but these do not cause diplopia. If windshield curvature is a necessity due to aerodynamics or other considerations, then materials and manufacturing processes must be developed that provide consistent curvature and thickness so that refractive effects can be held within a small enough tolerance for generic optical compensation to be applied without tailoring HUDs to each individual aircraft.

A second part of the physical/optical integration is determination of the losses in visual capability due the optical elements located between the pilot's eyes and targets or other objects in the outside world that he is trying to visually detect. First, types of targets to be detected and acceptable minimum target detection ranges should be established through mission analyses. Once these parameters are established, the acceptability of system losses and the resultant capability of the system to meet these requirements can be established early in the program, using prototype optical elements. Application of contrast sensitivity analysis, as discussed in the previous section, to system target detection range capability can be established in a ground test environment. Here, the results can be effectively measured, as opposed to a flight test environment which relies heavily on pilot opinion and only discovers problems late in the development process.



HUD PHYSICAL INTEGRATION LIMITATIONS

FIGURE 1

FUTURE DEVELOPMENT TRENDS FOR HEAD-UP DISPLAYS

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ABSTRACT

The development of diffraction optics to provide the largest possible Field Of View (FOV) has been, and will continue to be, the most difficult and important area of HUD design. As larger FOV's are developed, greater demands will be placed on display resolution. The display of grey scale video places increased demands on improved display brightness. Significant reliability improvements are also needed. This paper outlines current state-of-the-art and indicates potential future improvements that can be made in these areas.

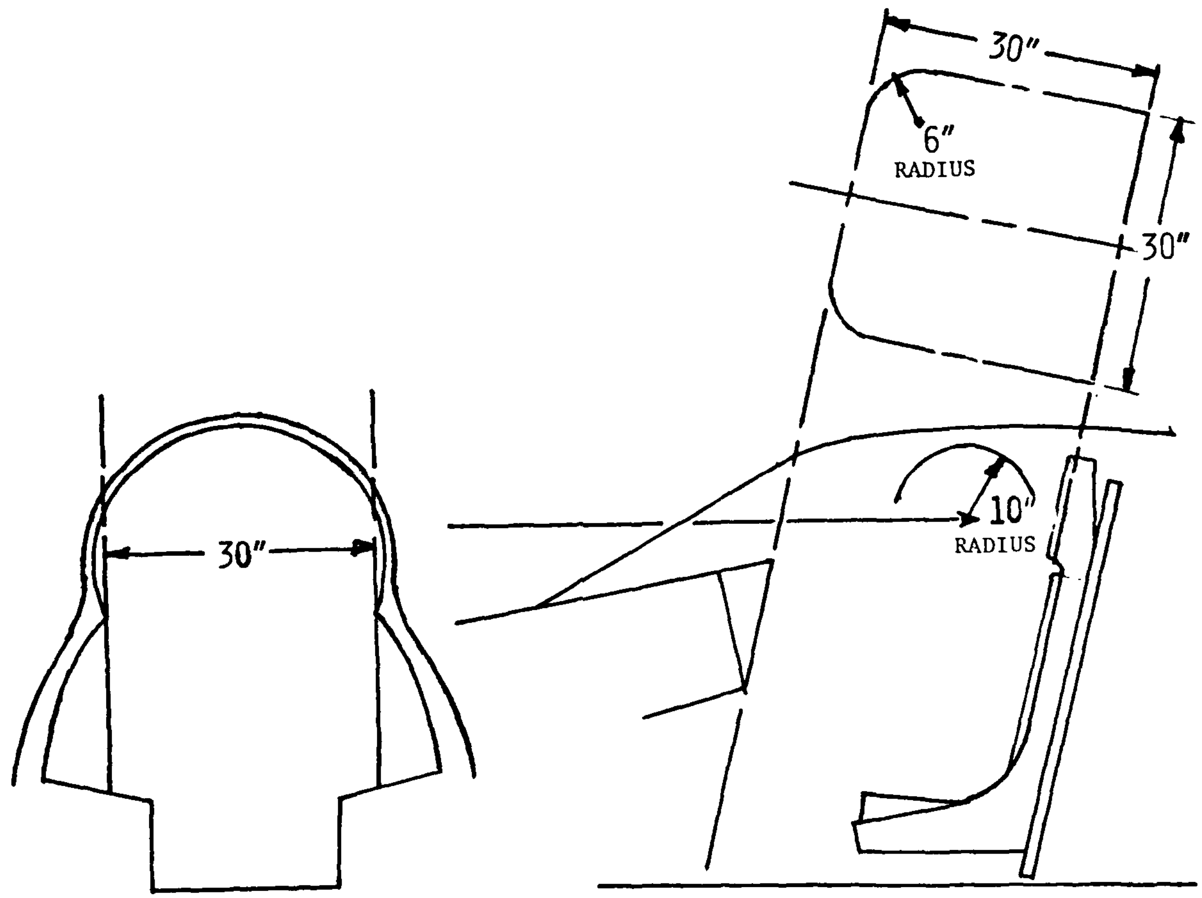
OVERVIEW

The optical area is currently the most difficult and important area of HUD design. Increased mission needs require that HUD's be built which can provide larger fields of view per unit volume. For example, the LANTIRN mission requires a 20°x30° field of view.[1] Indications from the users are that much wider fields-of-view are desirable, i.e., 45° or even as much as 180°. Conventional optics are being supplemented with diffraction optics in attempts to meet these requirements. Currently, three U.S. companies and one European company are pursuing diffraction optics HUD designs. In addition to Wide Fields Of View (WFOV), diffraction optics are capable of providing greater transmissivity or "see through" of the real world scene, although this capability is not achieved in all configurations.

As greater FOV's are achieved by improved optics design, displays of greater resolution will also be required. Some idea of the relative improvement required may be obtained by comparing a 30 degree FOV HUD with a 5x5 inch direct view display (DVD). The DVD subtends about 10 degrees at a nominal 29 inch viewing distance. Then, for equivalent resolution criteria, the 30 degree HUD would require six times the display resolution (pixels) of a 5x5 inch DVD (20°x30°/10°x10°).

Improved display brightness will also be required due to the use of HUD's for display of raster video, such as Forward Looking Infrared (FLIR), in cases where the raster video must be seen under daylight conditions. Even for a night system, this condition occurs during training exercises. It is estimated that 85,000 foot lamberts display raster brightness would be required to attain a 6/1 contrast ratio in a diffraction optics HUD combiner (of 90% transmittance), in 10,000 F.L. ambient. Currently, the LANTIRN HUD Cathode Ray Tube (CRT) raster brightness is specified as 1,000 foot lamberts, thus, almost two orders of magnitude brightness improvement are needed.

An integral part of the display problem is the need for reliability improvement. Presently fielded HUD systems have Mean Time Between Failures (MTBF) in the range of 50-125 hours. Solid state displays, which operate at low power/voltage levels, do not require high voltage power supplies and analog circuitry. Thus, they offer significant potential for MTBF improvement (i.e., 300-400% for the Display Unit).



EJECTION ENVELOPE

FIGURE 2

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FUTURE DEVELOPMENT TRENDS FOR HEAD-UP DISPLAYS

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The development of diffraction optics to provide the largest possible Field Of View (FOV) has been, and will continue to be, the most difficult and important area of HUD design. As larger FOV's are developed, greater demands will be placed on display resolution. The display of grey scale video places increased demands on improved display brightness. Significant reliability improvements are also needed. This paper outlines current state-of-the-art and indicates potential future improvements that can be made in these areas.

OVERVIEW

The optical area is currently the most difficult and important area of HUD design. Increased mission needs require that HUD's be built which can provide larger fields of view per unit volume. For example, the LANTIRN mission requires a 20°x30° field of view.[1] Indications from the users are that much wider fields-of-view are desirable, i.e., 45° or even as much as 180°. Conventional optics are being supplemented with diffraction optics in attempts to meet these requirements. Currently, three U.S. companies and one European company are pursuing diffraction optics HUD designs. In addition to Wide Fields Of View (WFOV), diffraction optics are capable of providing greater transmissivity or "see through" of the real world scene, although this capability is not achieved in all configurations.

As greater FOV's are achieved by improved optics design, displays of greater resolution will also be required. Some idea of the relative improvement required may be obtained by comparing a 30 degree FOV HUD with a 5x5 inch direct view display (DVD). The DVD subtends about 10 degrees at a nominal 29 inch viewing distance. Then, for equivalent resolution criteria, the 30 degree HUD would require six times the display resolution (pixels) of a 5x5 inch DVD (20°x30°/10°x10°).

Improved display brightness will also be required due to the use of HUD's for display of raster video, such as Forward Looking Infrared (FLIR), in cases where the raster video must be seen under daylight conditions. Even for a night system, this condition occurs during training exercises. It is estimated that 85,000 foot lamberts display raster brightness would be required to attain a 6/1 contrast ratio in a diffraction optics HUD combiner (of 90% transmittance), in 10,000 F.L. ambient. Currently, the LANTIRN HUD Cathode Ray Tube (CRT) raster brightness is specified as 1,000 foot lamberts, thus, almost two orders of magnitude brightness improvement are needed.

An integral part of the display problem is the need for reliability improvement. Presently fielded HUD systems have Mean Time Between Failures (MTBF) in the range of 50-125 hours. Solid state displays, which operate at low power/voltage levels, do not require high voltage power supplies and analog circuitry. Thus, they offer significant potential for MTBF improvement (i.e., 300-400% for the Display Unit).

This paper is written for practitioners in the field. Those readers unfamiliar with the subject should consult references 2, 3 and 4.

HUD OPTICS

The attainment of WFOV would present no significant problems if long optical path lengths were available, because this implies large F numbers and lenses that are easy to produce. However, the HUD installation in military aircraft is constrained both by path length and physical obstructions, as shown in Figure 1, to short paths and low F number optics.

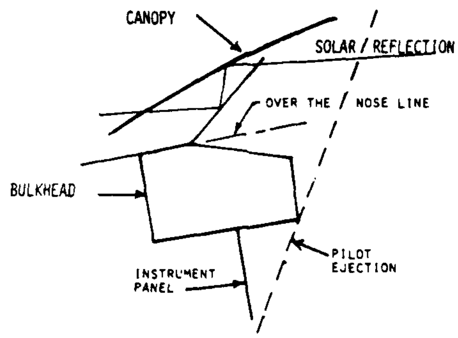

FIGURE 1 PHYSICAL CONSTRAINTS ON HUD DESIGN

In most HUD installations, the aircraft canopy design has already been locked in concrete before the HUD design is conceived. In future aircraft these designs should proceed in parallel so that problems such as "double imaging" can be avoided. In addition, the canopy could be designed to provide more clearance in the vicinity of the combiner, in order to increase HUD vertical FOV.

Development of a windshield system requires consideration of many factors. These are; aerodynamic shape, materials for operational durability and protection from aerodynamic heating, deice - defog capability, aircrew visual task performance, protection against nuclear flash and Electro Magnetic Pulse (EMP), aircrew escape, birdstrike protection, radar cross section reduction, and windshield cost. As a result of all these factors, windshield development generally takes about five years. Therefore, HUD requirements must be made known as early as possible, in order to realize improved HUD/windshield interfaces.

CURRENT STATUS OF OPTICS

Currently, there are two primary design approaches for attaining WFOV diffraction optics HUD performance, as shown in Figures 2A and 2B. For convenience, these are designated the Three Element Combiner (TEC) and the Single Element Combiner (SEC) approaches.

Table I compares the TEC and SEC HUD's with a HUD of conventional refractive design now being used on the Advanced Fighter Technology Integration (AFTI) program. The FOV's of refractive and reflective HUDs are not directly comparable, as explained later in this paper. As discussed in the previous papers, the TEC experienced a number of problems and is now being redesigned. The redesigned TEC is also shown in Table I.

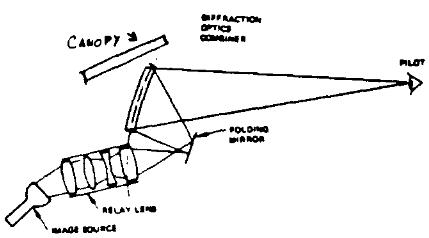

FIGURE 2A SINGLE ELEMENT COMBINER, SEC

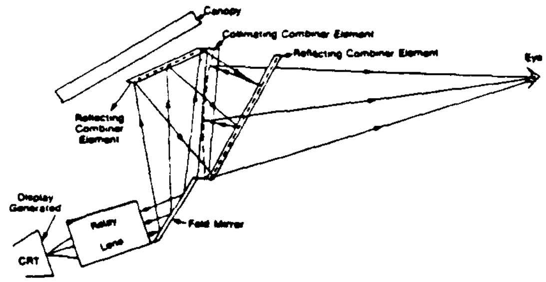

FIGURE 2B THREE ELEMENT COMBINER, TEC

TABLE 1 - COMPARISON OF WIDE FIELD-OF-VIEW HUD OPTICS

	TEC	REDESIGNED TEC	SEC	REFRACTIVE HUD (AFTI)
FLIGHT TESTED?	YES, F-16 TEST	NO, TEST AUG 83 (F-16)	YES, F-18 TESTS	YES, F-16 TESTS
UNWANTED REFLECTIONS OF STRAY LIGHT	UNACCEPTABLE TO F-16 PILOTS, ACCEPTABLE TO A-10 PILOTS	EXPECTED TO BE LESS PROMINENT	ACCEPTABLE IN F-18 TESTS	ACCEPTABLE IN F-16 TESTS
TARGET DETECTION PENALTY	ANALYSIS OF CONTRAST SENSITIVITY DATA, TAKEN ON LANTIRN, AFTI AND F-16 PRODUCTION HUDS INDICATES OVERALL EQUIVALENT PERFORMANCE			
OPTICAL ABERRATIONS, COMPLEXITY OF OPTICS	QUASI-AXIAL DESIGN. LESS COMPLEX	QUASI-AXIAL DESIGN. LESS COMPLEX	OFF-AXIS DESIGN. MOST COMPLEX	ON-AXIS DESIGN. LEAST COMPLEX
WIDE FOV CAPABILITY	MEETS LANTIRN SPECIFICATION 20° X 30°	SMALLER COMB VIEWING DISTANCE 4 INCHES LESS	SLIGHTLY LESS FROM VIEWING POSITION OF LANTIRN SPEC.	NOT ONE TO ONE COMPARABLE. VIEW DIST. 4 INCHES LESS
SEE THROUGH TRANSMISSION	70%	70%	90%	70%

Thus, the current status of wide FOV HUD's is;

(1) The requirement to develop WFOV has led to increased optical aberrations to be corrected somewhere in the optical design. Because the TEC has fewer aberrations, it was selected for wide FOV development.

(2) The initial TEC HUD had serious problems with pilot acceptability and is now being redesigned to minimize these problems. In the interim, refractive (AFTI-like) HUDs will be used to meet F-16 aircraft production schedules.

(3) The SEC approach, although having more aberrations to be corrected, has few problems with pilot acceptability. The SEC HUD, flown in the F-18, was developed under an AFWAL Materials Laboratory contract. A preliminary design was also flown in the Swedish Viggen aircraft. A production contract has been awarded for the Swedish JAS 39 combat aircraft.

(4) Experience with the TEC has verified that objective engineering tests should be conducted on prototype units prior to commitments being made to production programs. Preliminary flight testing may also be required, but should be accomplished in an environment where engineering changes can be made without the pressure of production schedules. These preliminary tests are not a substitute for operational flight tests, to which the HUD must ultimately be subjected in any case.

POTENTIAL OPTICS IMPROVEMENTS

The best of both worlds (TEC and SEC) would be realized if a SEC wide FOV HUD could be designed with reduced aberrations. For example, the mirror could be moved further forward, to lengthen the optical path as shown in Figure 3.

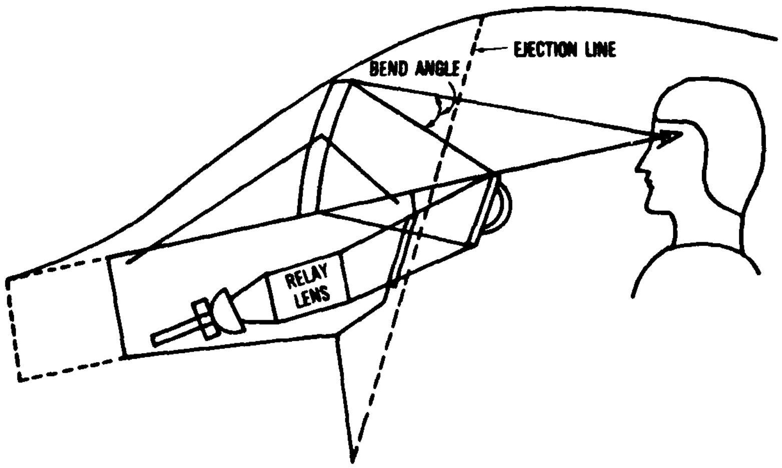

FIGURE 3. EXAMPLE OF A NOVEL DESIGN, THE RETRACTABLE MIRROR HUD

Since the mirror would necessarily lie beyond the pilot ejection line, a mechanical method would have to be developed for retracting it within a few seconds, to permit pilot ejection. This design would allow the exit pupil size to be increased, since the "bend angle" of the light rays incident on the combiner would be reduced and, consequently, the angular FOV increased. Alternatively, the bend angle could remain the same, the tilt of the combiner reduced, and the vertical FOV increased.

The ideal location for the mirror, to minimize aberrations, is to place it directly in the field of the combiner. Then, the mirror would become a beamsplitter and a totally on-axis design might be possible. The disadvantages of this approach are reduced transmission of the real world scene and the possible introduction of unwanted reflections of stray light.

The principal advantage of diffraction optics over conventional optics is that they permit additional complexity to be added to the construction optics rather than to the HUD optics. This is shown in Figure 4. Since only a few sets of construction optics are required, as opposed to one set of HUD optics for each aircraft, more complex systems should be realizable (for equivalent cost) with diffraction optics.

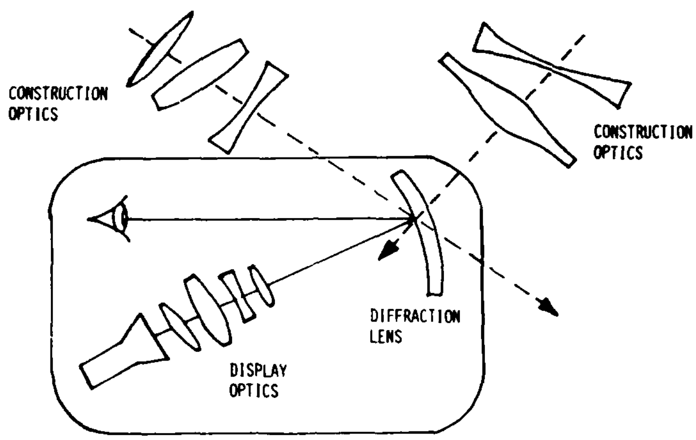

FIGURE 4 THE ADVANTAGE OF DIFFRACTION OPTICS IS THAT COMPLEXITY MAY BE ADDED TO THE CONSTRUCTION OPTICS WHICH ARE NOT PART OF THE FLYABLE SYSTEM.

Glass optics are currently used to form the construction beams for holographic combiners. This approach is limited by the complexity of the optical elements which can be built. A more general approach is to use Computer Generated Holograms (CGH) in the construction optics. CGH's can generate wavefronts of more arbitrary shape, than are realizable with glass optics. An initial step in this direction was taken by the Environmental Research Institute of Michigan (ERIM), through a program sponsored by the Avionics Laboratory in 1981.[5] It appears that CGH's may ultimately resolve many of the problems currently being encounted in WFOV HUD design.

Pilot Viewing/HUD Interface.

Neither the total nor the instantaneous fields of view of reflective and refractive HUD's are similar in shape. This point is illustrated in Figures 4 and 10 of Chorley's paper.[2] The total FOV of the reflective HUD is diamond shaped, while that of the refractive HUD is triangular. The refractive HUD has a greater solid angle, over which some portion of the (instantaneous) FOV may be viewed, than does the reflective HUD. These points are illustrated in Figure 5.

Considering these differences, "How should the exit pupil viewing characteristics be specified?" To answer this question we begin by assuming that it is possible to determine:

(a) The expected range of seating accommodation required for all pilots who will fly the aircraft.

(b) The maximum expected interpupillary spacing plus desired head motion up/down, left/right and forward/back.

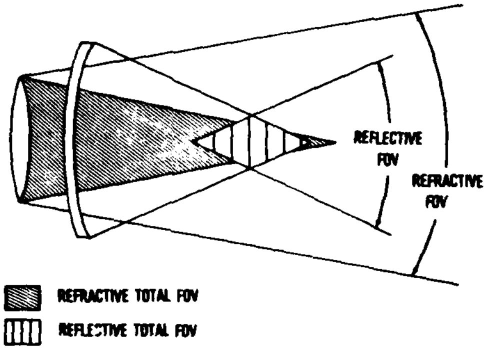

FIGURE 5. COMPARISON OF REFRACTIVE AND REFLECTIVE OPTICS FOV'S. THE SIZE OF THE REFRACTIVE FOV'S ARE EXAGGERATED TO ILLUSTRATE APPROXIMATELY EQUAL TOTAL FOV VIEWING CHARACTERISTICS

From these data, the size, shape and location of the pilot's head motion box can be established. The ideal pilot accommodation occurs when the HUD total FOV completely encloses the head motion box. However, this condition requires larger FOV's than are generally attainable. Nevertheless, it is desirable for the total FOV to enclose as much of the head motion box as possible.

A proposed limiting criterion is to specify the percentage of the total FOV which is viewable by all (or some) pilots without head motion. This criterion is determined by the overlap of the head motion box with that portion of the total FOV in which a pilot with Maximum (or minimum) Interpupilary Spacing (MIS) can just see, or can easily see, the total FOV with both eyes. The results of applying these criteria to reflective and refractive HUD's are shown in Figure 6. This problem is illustrated here as two dimensional, although it is actually three dimensional. Therefore, the proposed specification is the percentage of the total FOV volume, which is enclosed within the volume of the head motion box; the fore and aft boundaries being determined by the MIS.

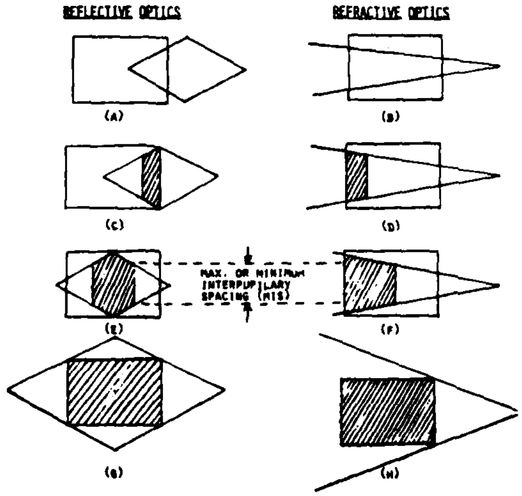

FIGURE 6 PERCENTAGE OVERLAP WITH BINOCULAR VISION (A) AND (B) - ZERO, (C) AND (D) - 15 %, (E) AND (F) - 40%, (G) AND (H) - 100%. THE HEAD MOTION BOX IS ASSUMED TO BE RECTANGULAR, BUT MAY ACTUALLY HAVE A MORE COMPLEX SHAPE.

HUD Displays.

A high brightness, high resolution CRT is currently under development through contract with the Avionics Laboratory. This improved CRT will have a three inch diameter viewing area and be compatible with a P43 spectrum, so that it can be used in a diffraction optics HUD. The expected raster brightness is 10,000 foot lamberts or more and spot size should be on the order of two mils. This brightness is about an order of magnitude better than current state-of-the-art.

For the past decade, the Systems Avionics Division of the Avionics Laboratory has sponsored the development of dynamic scattering Liquid Crystal Display (LCD) technology. About half of the funding has been used for the development of applications demonstrators. Emphasis has been on more difficult applications, such as the HUD and high brightness Direct View Displays (DVD). The LCD is a reflective solid state display. When used in conjunction with arc lamp illumination, very high brightness has been demonstrated (5,500 foot lamberts raster brightness over a 49 square inch viewing area with 20/1 contrast ratio, using a 100 watt arc lamp). For a HUD display of 4.175 square inch viewing area (LANTIRN raster area), this translates into 64,500 foot lamberts raster brightness. The other development area being pursued with this technology is increased resolution. Current state-of-the-art, for a single LCD module, is 240x320 pixels (76,800). Four of these modules are required for compatibility with 525 line video. Optical image combining is being used to provide modular improvements in resolution (see Figure 7).

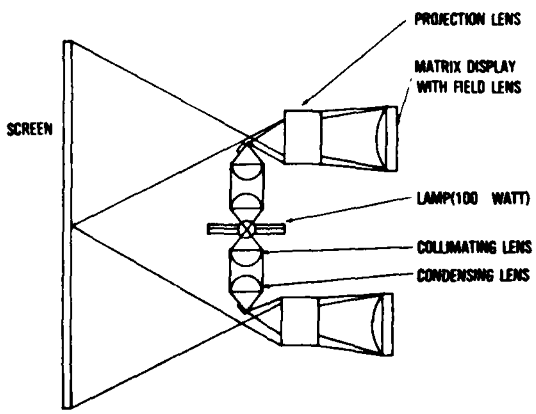

FIGURE 7. OPTICAL COMBINING OF LCD IMAGES

Optical projection of solid state reflective display images is a general technique which can be adapted to solid state displays other than the LCD. Very high brightness can be achieved using non-emissive displays with arc lamp illumination. The success of this approach is attributed to the fact that light generation and intensity modulation are performed by two separate devices. Thus, brightness can be optimized independent of writing speed.

An advanced technology HUD was designed and built for the Avionics Laboratory under contract with Hughes Aircraft. In this design, an LCD was integrated with diffraction optics.[6] In addition, a high brightness color DVD has been built and demonstrated using the same LCD module. This color display was built under a Navy contract.

Because of the modular nature of the LCD's, the possibility exists to adapt a few basic modules to a variety of applications, as show in Figure 8.

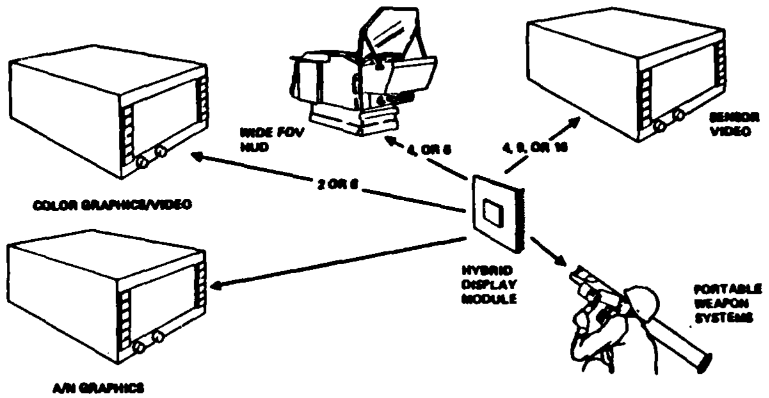

FIGURE 8 APPLICATION OF LCD VARIOUS DISPLAYS

A comparison of the improved CRT and the LCD technology is shown in Table 2. The LCD/Solid State Display is seen as providing higher brightness and reliability in the long term. The CRT technology will provide more near-term improvements of lesser magnitude.

TABLE 2 - CRT/LCD COMPARISON FOR HUD APPLICATIONS

	IMPROVED CRT	LCD
RASTER BRIGHTNESS FOR 4.175 SQUARE INCH VIEWING AREA. (CURRENTLY 1,000 F.L.)	10,000 F.L. ANALYSIS BASED ON SMALLER TUBE DEMONSTRATION	64,500 F.L. ANALYSIS BASED ON LARGER VIEWING AREA DEMONSTRATION
RESOLUTION	2 MIL SPOT SIZE	2.8 MIL PIXEL SIZE 1.9 MIL IN 4 YEARS
DISPLAY UNIT RELIABILITY	20-50% IMPROVEMENT AT CURRENT BRIGHTNESS LEVELS, BUT NOT AT 10,000 F.L.	300-500% PRIMARILY DETERMINED BY ARC LAMP. NOT BRIGHTNESS DEPENDENT.
STROKE WRITING	NOT REQUIRED	NOT REQUIRED
POTENTIAL USE IN PRODUCTION HUD	2 - 3 YEARS	6 - 7 YEARS
OTHER DISPLAY APPLICATIONS	COLOR CRT, HEAD DOWN DISPLAYS, etc. EACH DESIGNED FOR SPECIFIC APPLICATION	COLOR DISPLAY, HEAD DOWN DISPLAYS, ELECTRONIC/ FILM ANNOTATION, WEAPON SIGHT ETC. TWO OR THREE LCD MODULES USED FOR ALL APPLICATIONS.

SUMMARY

Figure 9 summarizes HUD development trends anticipated at this time. It is also possible that a two element combiner HUD may be a contender in the future.

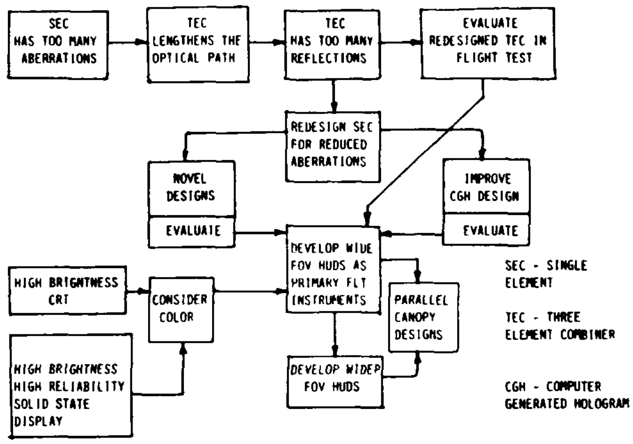

FIGURE 9 FUTURE DEVELOPMENT OF REFLECTIVE HUD'S

ACKNOWLEDGEMENTS

Although solely responsible for the views presented in this paper, the author wishes to thank Mr. Jim Byrd, ASD/ENAIC and Mr. Bill Augustine, AFWAL/FIGR, who reviewed the manuscript and made helpful suggestions and comments. Mr. Ralph Speelman, AFWAL/FIEA provided information on windscreen system design.

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BIOGRAPHIES

Wayne L. Martin has been an Engineering Research Psychologist with the Human Engineering Division of the Air Force Aerospace Medical Research Laboratory since 1967. His present assignment as the technical director and assistant chief of the Visual Display Systems Branch capitalized on a rich practical background as both airman and officer in aircraft instrumentation and avionic systems maintenance, coupled with academic experience amounting to the Master's Degree, plus three years in Experimental Psychology. Among his credits are research programs in information management for logistic systems, aircraft maintenance and C^3 systems design, as well as research in basic vision, matrix element displays, deep space satellite detection, head-up displays, night vision systems, night attack performance assessment and color displays. Wayne is a member of both the National and Southern Ohio Chapters of the Human Factors Society, Association of Aviation Psychologists, and the Society for Information display.

Richard D. Lee graduated from the University of Toledo in 1969 with a BS degree in Electrical Engineering. He began work that same year with the Avionics Engineering Directorate of the Aeronautical Systems Division. He received an MS degree in Electro-Optics from the Air Force Institute of Technology and has performed post graduate level study in the Electro-Optics field. His current duties in the Electro-Optics branch at ASD include supporting the LANTIRN program office in the field of diffractive optics for the Head-Up-Display.

Dr. Harry Lee Task received his BS in 1968 from Ohio University and MS in 1971 from Purdue University in physics. He received his MS and PhD in Optical Sciences from the University of Arizona, Optical Sciences Center in 1978. Dr. Task has worked for the Air Force Aerospace Medical Research Laboratory at Wright-Patterson AFB, since 1971. Areas of research interests include: Visual Image Display Quality, Windscreen Optical Quality, Night Aid Visual Systems and Lighting. Dr. Task has produced several publications and patents in these and related areas.

Lt Col Louis V. Genco received his undergraduate education at Loyola University of Chicago, his Doctorate in Optometry from Illinois College of Optometry, and an MS in Physiological Optics from the Indiana College of Optometry. In 1978, after 14 years of Air Force clinical and teaching experience, Lt Col Genco was assigned to the Air Force Aerospace Medical Research Laboratory, where he is now the Chief, Crew Systems Effectiveness Branch, Human Engineering Division. Lt Col Genco is deeply involved with investigating the effects of manipulating various visual parameters on aircrew performance. The efforts include studies of optical enhancements to both daytime and nighttime aircrew vision as well as the effects of various optical parameters induced by aircraft windscreens, canopies, head-up displays and other optical devices. Lt Col Genco is a fellow of the American Academy of Optometry and a charter member of the Armed Forces Optometric Society.

Mr. Wilson is a senior Avionics Systems Engineer within the Integrated Controls and Displays Branch at WPAFB. He has been active in developing the architecture for and development of complete control and display subsystems. His most recent work was the B-52 Offensive Avionics System (OAS) Controls and Displays. Mr. Wilson holds a BS Degree in Systems Engineering from Wright State University.

Dr. H. C. Self an engineering research psychologist in the Visual Display Systems Branch at AFAMRL, Wright-Patterson Air Force Base, specialized in vision and perception. He received his PhD in experimental psychology at the University of Texas. Formerly with the U.S. Naval Research Laboratory, he came to the Air Force to do basic and applied research on target detection and recognition with the unaided eye, sunglasses, CCTV, radar, IR, photography, etc. His work includes the design, analysis testing and evaluation of airborne and ground-based equipment and man-machine systems.

Arthur P. Ginsburg received the B.S.E.E. degree from Widener College in 1969, the M.S.E.E. from the Air Force Institute of Technology in 1971, and the Ph.D. in Biophysics in 1980 from the University of Cambridge. He is presently a Major in the Air Force, serving as Director of the Aviation Vision Laboratory of the Air Force Aerospace Medical Research Laboratory. Major Ginsburg's main interest is the application of linear systems analysis to obtain filter characteristics of overall and individual mechanisms of the human visual system. This research views visual perception as a filtering process and is concerned with basic and applied problems in visual standards, operator performance, display quality, and visual target acquisition. Major Ginsburg is a member of Tau Beta Pi, Sigma Pi Sigma, Sigma Xi, the Optical Society of America and the American Association for the Advancement of Science.

BIOGRAPHIES (CONT'D)

Ronald W. Schwartz is a senior crew station design engineer in the Crew Station and Escape Branch of the Directorate of Equipment Engineering for Aeronautical Systems Division. He has a Bachelor of Science in mechanical engineering and a Master of Science in engineering management. His twenty years experience in crew station design and control display systems includes experience in the Flight Dynamics Laboratory in display concept design and studies on control display subsystem design for a tactical V/STOL aircraft. Since moving to ASD Engineering seventeen years ago, he has had primary responsibility for crew station design on the F-15, A-10, A-7, and HH-53. He is currently responsible for the crew station design on the C-17 and HH-60D.

Mr. John F. Coonrod has 26 years experience in the display field. He has a BSEE from Purdue University. He has worked for the Civil Aeronautics Administration, the US Naval Avionics Facility (NAFI), Aeronautical Systems Division (ASD) and the Air Force Avionics Laboratory. While at ASD, he worked on the F-111D Mark II Avionics System and the B-1 Offensive Avionics. His recent experience includes eight years at the Avionics Laboratory, where he has been the project engineer on programs involving solid state liquid crystal displays and diffraction optics for application to head-up and head-down displays. Most recently, Mr. Coonrod has participated in joint AFWAL/ASD programs including the F-16E Technology Assessment and the LANTIRN Independent Review Team.

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